1

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AN EVALUATION OF AIRCRAFT CRT AND DOT-MATRIX DISPLAY LEGIBILITY REQUIREMENTS

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13. ABSTRACT *(Maximum 200 words)*
Pilot satisfaction with the legibility performance of the absorption bandpass filtered green P-43 phosphor cathode ray tube (CRT) electronic displays employed in the F-15, F-16 and F-18 aircraft, prior to 1980 has been used in this report as a basis for establishing minimum luminance and contrast requirements for both CRT and dot-matrix electronic aircraft displays. The data drawn on and the methods used to derive the alphanumeric, graphic and video information legibility requirements that should as a minimum be met by aircraft electronic display portrayals under direct sunlight, glare source and other high ambient viewing conditions are described. The sunlight readability/legibility requirements and tests of the night vision imaging system (NVIS) compatibility specification MIL-L-85762 were in part founded on the data contained in this report.

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FORWARD

The present report is a modified version of an internal working report originally prepared by Dr. Keith T. Burnette in 1980 under Contract F33615-78-C-3614. The purpose of that report was to provide background information to support the development of dot-matrix display legibility specifications then being formulated by the Tri-Service Airborne Display Technology Working Group.

The conversion of the report to make it suitable for publication as a USAF Technical Report was undertaken in 1985 as a consequence of the increasing consideration then being given to the expanded use of dot-matrix displays for the presentation of aircraft cockpit information, and due to the fact that the information presented in the report was used as a partial basis for the sunlight readability/legibility requirements stipulated by the author in MIL-L-85762. Revised as time permitted between other higher priority efforts, all of the changes to the report were not completed until 1991. The intent of the changes was restricted primarily to publication format issues including formal illustrations and to text changes to clarify the report's information content. Footnotes have been added where the information presented in the original report was considered to be insufficiently defined. The reader is none the less advised to bear in mind that the time reference of the report and in particular the display technology described is that of the 1980 time period.

The preparation of this report for publication was initiated by Burnette Engineering for the Flight Dynamics Laboratory, U.S. Air Force Wright Aeronautical Laboratories, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, under Contract Number F33615-84-C-3627. As a result of a recent reorganization the name of the organization responsible for the contract has been changed to the Crew Systems Concepts Group, Crew Systems Development Branch, Wright Laboratories, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Mr. George W. Palmer was the Air Force Project Engineer during the period of the contract, which was conducted as a part of a program of advanced display design and development managed for the USAF by Mr. Walter Melnick.

Dr. Keith T. Burnette served as the principal investigator for Burnette Engineering during the period of this effort.

SUMMARY

This report endeavors to establish legibility requirements for head down dot-matrix displays intended to portray alphanumeric, graphic and video information. Meeting or exceeding the image legibility that has been achieved on the F-15, F-16 and F-18 aircraft CRT displays is the criteria used for establishing the dot-matrix display legibility requirements. These particular CRT displays have been selected for the comparison both because of the bubble canopy design of the aircraft and because the pilots using them consider their legibility to be adequate under the full range of ambient illumination conditions experienced in flight. Requirements which appear to be excessive, based on known human visual perception requirements, are identified. A summary of CRT display legibility data upon which the evaluation of the CRT and dot-matrix display legibility requirements is based is contained in an appendix to the report. The report attempts to provide a sufficient description of the legibility requirements and rationale used to arrive at them to permit the reader to make realistic evaluation of their validity.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT)

TABLE OF CONTENTS (CONT)

LIST OF FIGURES

LIST OF TABLES

SECTION 1

INTRODUCTION

Optically filtered P-43 phosphor cathode ray tube (CRT) displays have been used successfully by both the USAF and the Navy in clear canopy fighter aircraft such as the F-14, F-15, F-16 and F-18. Although pilot experience with these displays is limited in the case of the F-16 and is restricted to flight test in the F-18, the legibility of head down information achieved on these displays is generally considered to be satisfactory by the pilots flying them.* The objective of this report is to provide legibility requirements data for the graphics and video information depicted on these aircraft CRT displays and then using this as a basis establish minimum legibility requirements for comparable information to be presented on dot-matrix flat panel displays.

The comparison of dot-matrix with stroke or raster written imagery is most conveniently carried out by comparing each to what will be referred to as "ideal" (continuous spatial luminance profile, high image quality) imagery, like that obtained by using engraving or photographic processing techniques. A continuous image alphanumeric character is illustrated in Figure 1. When the stroke width (SW) of a uniform luminance alphanumeric character, such as the one illustrated, satisfies the condition:

$$0.12h \leqq SW \leqq 0.2h \qquad (1)$$

its legibility is optimized and it will be referred to as an "ideal" alphanumeric character.

Reducing the stroke width of a fixed critical detail dimension, cd, alphanumeric character below its $SW_I = 0.12h$ ideal character limit requires a proportionate increase in the character's difference luminance, ΔL, where

$$\Delta L = L_S - L_D \qquad (2)$$

in order to maintain constant image legibility. In Equation 2, L_S is the symbol luminance (i.e., measured with a small area aperture probe) under a stipulated ambient illumination test condition and L_D is the display background luminance measured in the presence of the same ambient.

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*Pilot acceptance of the legibility of the cited displays has continued to be excellent up to the present time.

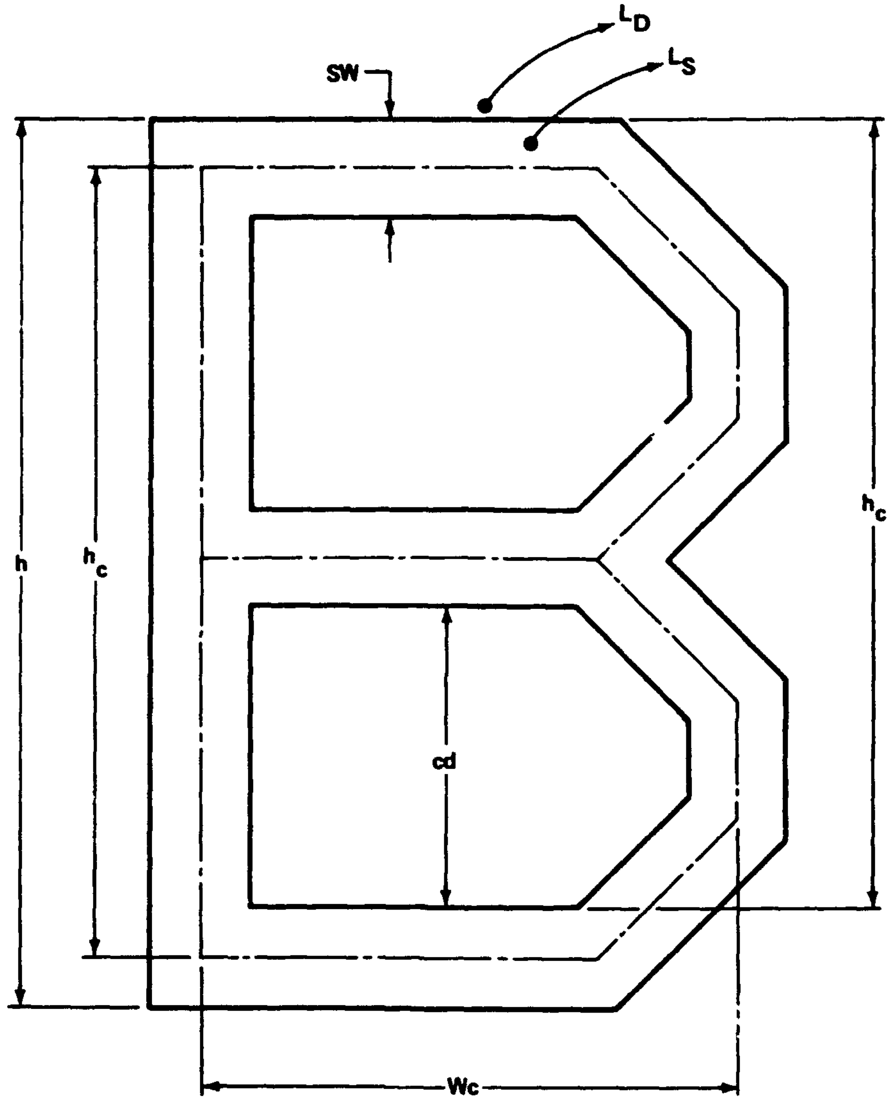

Figure 1. Continuous Image Alphanumeric Character

As a second order effect, when the stroke width is reduced but the height parameter, h_c, is held fixed, the symbol's critical detail dimension, cd, is increased. This causes the narrow stroke width character to be perceived as being larger than its ideal continuous stroke counterpart and reduces the luminance compensation required for equal character legibility to less than the linear increase that would have been needed had the critical detail dimension been held fixed.

In this report the legibility of both dot-matrix and CRT written characters will be related independently to the legibility of "ideal" continuous characters and thereby to each other. Alphanumeric characters have been selected for this comparison because they represent one of the most difficult graphics display visual perception tasks a pilot encounters. Unlike the more pictorial information presented using graphics techniques, alphanumerics must be completely legible in order for the information they convey to be perceived. Video imagery will also be treated in this report, however, in this case the method of accomplishing the comparison between dot-matrix and CRT imagery is not as clearly defined, due to the more limited information available on video image perceptual requirements. The CRT display capabilities that will be compared to are contained in Appendix A which provides the basic legibility specifications and test results for state of the art aircraft CRTs used in the F-15, F-16 and F-18 multipurpose displays.

Due to past problems in achieving adequate graphics and video image legibility on aircraft CRTs, the emphasis of CRT display procurement specifications tends to be on providing sunlight display legibility. Two important recent additions to such specifications have been: (1) the use of an integrating sphere of 10,000 foot-Lamberts (fL) surface luminance in place of a 10,000 foot-candle (fc) illuminance spot source at an angle of 45° with respect to the display surface normal and (2) the specification of a minimum difference luminance level, ΔL, (i.e., see Equation 2) at which the display must be capable of being operated. The integrating sphere simulates the high ambient diffuse surround illumination conditions which are known to produce high reflected luminance levels from CRT displays in sun illuminated haze, mist or clouds. The minimum difference luminance requirement is imposed as a means of countering the legibility degradation caused by glare source induced veiling luminance when the sun is visible in the pilot's instantaneous field of view.

Virtually all forms of cockpit CRT display information must be perceptible to the pilot throughout the entire ambient illumination range from 10^{-6} fc to 10^{4} fc. At night the CRT information design and luminance control should be compatible with achieving a good tradeoff between pilot dark adaptation and display information legibility requirements. At the other end of the illuminance range many flight missions require sunlight legible graphics and sensor video information. Graphics information requirements in a 10,000 fc illuminance environment include flight control, navigation, communications, weapons, and system status information for example. Sensor video information requirements in a 10,000 fc viewing environment vary with aircraft mission but include: terrain following radar, air to air combat video, high altitude reconnaissance, clear weather use of FLIR for zoom magnification of targets, the location of refueling aircraft, search and rescue sensor data and weather radar detection of clear air turbulence and for cloud avoidance.

Dot-matrix displays clearly must be capable of satisfying the same requirements if they are to be acceptable for aircraft cockpit use.*

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*1991 Notation. The results derived in this report served as a partial basis for the Sunlight Readability/Legibility requirements specified subsequently in MIL-L-85762 *Night Vision Imaging System* (NVIS) Compatible Interior Aircraft Lighting. It should also be recognized that while 10,000 fc has been widely accepted as a high ambient illuminance test condition for the purpose of measuring and comparing the contrasts of aircraft electronic displays, the worst case illuminance levels actually encounted in aircraft can exceed this level, and in some instances by a large amount. Since the pilot's acceptance of the display legibility is based on the flight conditions actually experienced in fighter type aircraft, while using displays that meet the 10,000 fc MIL-L-85762 display legibility test requirements, adjustments to these test requirements for other types of aircraft, if justified, should be conducted using comparisons between the illumination conditions present in a bubble canopy fighter cockpit and those present in the different aircraft type of interest.

SECTION 2

PERCEIVED LUMINANCE REQUIREMENTS FOR IDEAL GRAPHICS CHARACTERS

Results of experimental tests show that a uniform luminance alphanumeric character set satisfying the stroke width requirement of Equation 1 and having sharply defined edge boundaries produce a given desired level of display image legibility with the minimum difference luminance setting (i.e., Equation 2) between the character and its background. In other words narrower stroke width characters can be made equal in legibility to the ideal character, but this requires a higher difference luminance setting for the non-ideal characters.

Equal image legibility performance is achieved for dimensionally ideal and non-ideal characters when the constant difference luminance of the ideal character equals the integrated spatial mean of the non-ideal character's difference luminance variation, the latter being spatially averaged over the area contained within the boundaries of the ideal character. This result is exact, subject to the provision that the critical detail dimensions of the ideal and non-ideal characters are equal. This is a very important experimental result since it allows equating the legibilities of characters that visually can appear quite different from one another. In particular it allows: (1) continuous uniform luminance characters, (2) CRT written characters and (3) dot-matrix characters to be described in terms of the perceived difference luminance of ideal characters, which in turn permits direct comparisons to be made. Conversion to the ideal character difference luminance formulation also has the advantage of permitting direct comparisons with existing published visual requirements data, since most of this data was generated using ideal or near ideal uniform luminance emissive, reflective or projected alphanumeric characters.

Mathematically the perceived difference luminance of an ideal character, ΔL_p, can be related to the difference luminance variation of a non-ideal character $\Delta L(x,y)$ by the equation

$$\Delta L_p = \frac{1}{A_e} \iint_{A_e} \Delta L(x,y)\, dx dy \qquad (3)$$

where A_e is the area of the ideal character. The area, A_e, in addition to being the actual area of the ideal character, will be referred to as the effective area of the non-ideal character for purposes of luminance averaging (i.e., Equation 3) to obtain the perceived luminance of the non-ideal character. Equation 3 expresses the visually observable result that characters having equal critical detail dimensions and equal values of ΔL_p are perceived as being of equal brightness even though differences in their physical geometries are visually evident.

The effective area A_e integrated over in Equation 3 may be interpreted either as: (1) the entire area encompassed within the boundaries of an ideal character, in which case ΔL_p is the average luminance for the entire character, or (2) A_e may be taken as a unit area portion of the character, causing ΔL_p to be capable of varying between different locations on the character due to display media induced variations in $\Delta L(x, y)$. In the former interpretation, an independent measure of display luminance uniformity would be required. In the latter case the boundaries of the unit area A_e must be carefully selected in terms of the spatial variation of $\Delta L(x, y)$ and the ideal character stroke width dimension

$$SW_I = 0.12h \tag{4}$$

defined in Section 1.

The difference luminance variation $\Delta L(x, y)$ in Equation 3 can be any arbitrary spatial luminance distribution. The perceived luminance characterization of $\Delta L(x, y)$ therefore provides a convenient universal variable, in terms of which the luminance requirements for any type of display can be specified.

SECTION 3

DETERMINATION OF PERCEIVED LUMINANCE REQUIREMENTS FOR GRAPHICS BASED ON AIRCRAFT CRT DATA

The intent of this section is to establish minimum perceived luminance requirements for aircraft cockpit alphanumeric information based on the recent favorable comments of pilots with respect to the legibility of CRT depicted alphanumeric character information. The resulting minimum perceived luminance requirements can then be used as a basis for establishing minimum difference luminance requirements for dot-matrix displays in a subsequent section.

3.1 Factors Influencing the Perceived Luminance of CRT Graphics

Applying luminance averaging to a CRT written line drawn in the y direction, Equation 3 may be written, on a per unit area basis, as:

$$\Delta L_p = \frac{1}{SW_I \ell} \int_{-\frac{SW_I}{2}}^{\frac{SW_I}{2}} \int_{-\frac{\ell}{2}}^{\frac{\ell}{2}} \Delta L(x,y)\,dy\,dx \qquad (5)$$

where ℓ is the length of the line that would be measured using a spatially scanned slit aperture photometer. If the CRT line measured is stroke written it may be assumed to be uniform in the y direction and Equation 5 further reduces to

$$\Delta L_p = \frac{1}{SW_I} \int_{-\frac{SW_I}{2}}^{\frac{SW_I}{2}} \Delta L(x)\,dx \qquad (6)$$

where $\Delta L(x)$ could be either established using the spatially scanned slit aperture photometer or the line spatial luminance profile could be assumed to be Gaussian, satisfying the equation

$$\Delta L(x) = \Delta L \exp\left[-\frac{x^2}{2\sigma^2}\right] \qquad (7)$$

The difference luminance ΔL is the peak line luminance to background luminance difference measured as described in Appendix A. The Gaussian spatial luminance profile of a CRT line is illustrated in Figure 2. Since contrast for a CRT is specified in terms of the

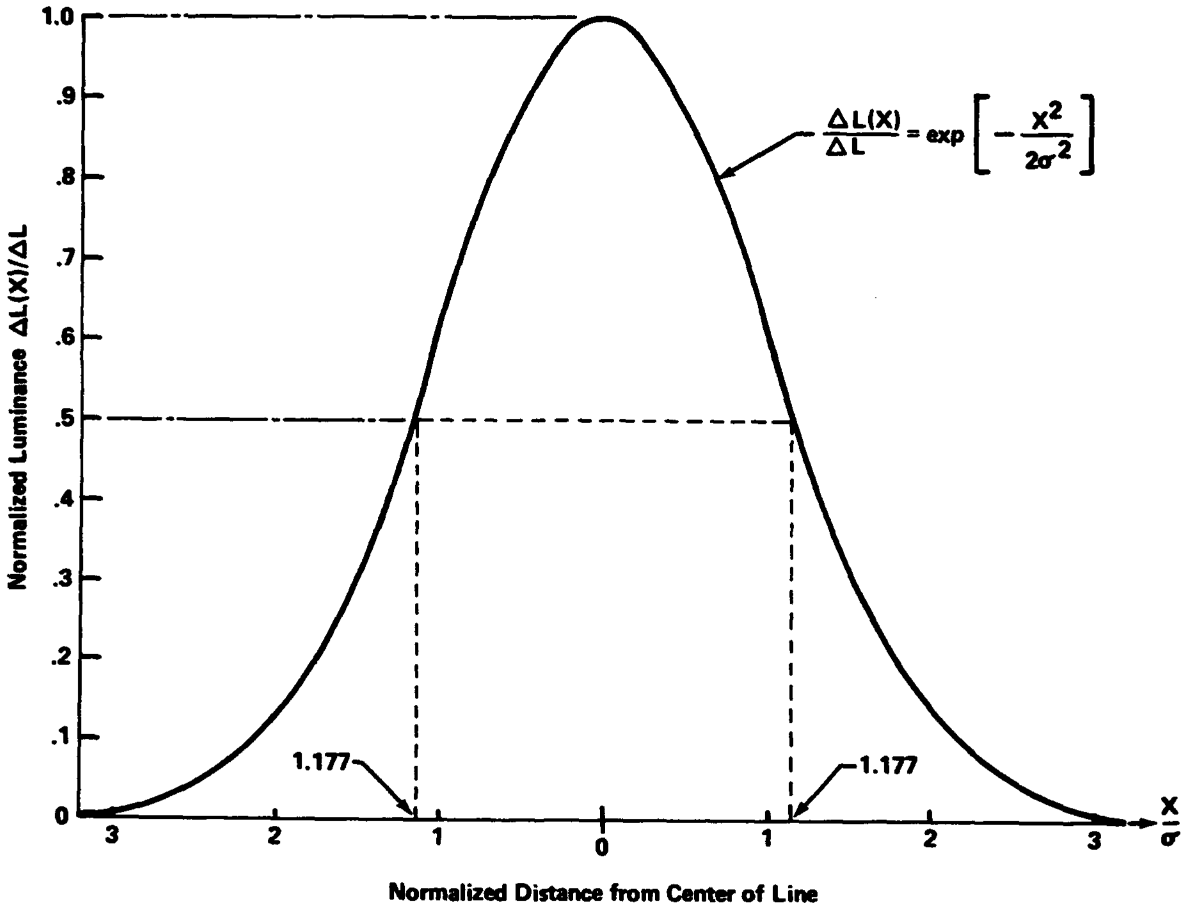


Figure 2. Gaussian Spatial Luminance Profile Approximation of CRT Line

line's peak difference luminance value, ΔL, the perceived luminance and contrast for an equivalent ideal character must be numerically less than the values quoted for a stroke written CRT.

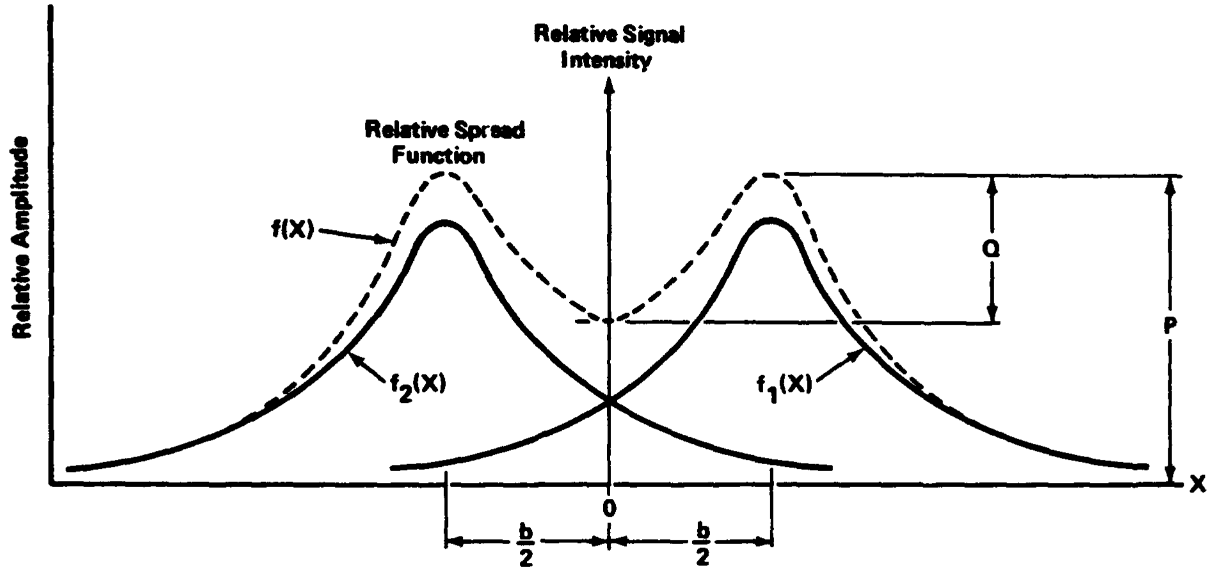
Characters written using a raster scanned CRT are the same as those obtained using stroke writing for the horizontal line segments. In the vertical direction the lines are formed by energizing the beam intensity at the same x coordinate location in a number of adjacent raster scan lines. Figure 3 illustrates the result of energizing two adjacent scan lines. The resulting luminance profile in the vertical (i.e., y) direction is illustrated in Figure 3 by the function f(x). The character formed by raster writing therefore has vertical lines having a periodic spatial luminance variation in the y direction in addition to the spatial luminance dependence in the x direction. The shape of raster generated vertical lines in the x scan direction can also differ significantly from their stroke written counterpart. The line width is not only influenced by the electron beam shape, phosphor light dispersion and photoemission characteristics, as it is for stroke writing, but is also influenced by the electron beam response times (i.e., display system electrical bandwidth limitations) associated with turning the phosphor on and off as the electron beam scans past the intended line coordinate. The Gaussian luminance profile of Figure 2 represents a lower limit on the width of a vertical raster written line, which could be achieved only in the limit of an infinitesimal electron beam pulse duration.

Beyond noting the differences between raster and stroke written characters as set forth in the preceding discussion, there is no value in making a detailed assessment of raster character legibility from a perceived luminance standpoint. The F-16 radar/EO display uses raster generated graphics but with a 8.26 mil center to center vertical separation between 6 mil half intensity diameter raster lines would produce a nearly uniform luminance profile in the vertical direction. This combined with a slight broading of the vertical line as compared to a horizontal line would cause the vertical line to have a slightly higher perceived luminance. For this reason, stroke and raster generated CRT characters will be treated as if they were stroke written.

3.2 Calculation of the Perceived Luminance of CRT Graphics Characters

Assuming that Figure 2 adequately represents the spatial luminance profile of a stroke written or raster written CRT line, then the 50% amplitude stroke width of the line is

$$SW_{.5} = 2.354\,\sigma \qquad (8)$$



$$f_1(X) = \exp\left[-\frac{(X-\frac{b}{2})^2}{2\sigma^2}\right]$$

$$f_2(X) = \exp\left[-\frac{(X+\frac{b}{2})^2}{2\sigma^2}\right]$$

$$f(X) = f_1(X) + f_2(X)$$

$$P = f(X = \tfrac{b}{2}) = 1 + \exp\left[-\frac{b^2}{2\sigma^2}\right]$$

$$Q = P - f(X = 0)$$

$$\text{Relative Modulation} = M = \frac{Q}{P} = 1 - \frac{2\exp\left[-\frac{b^2}{8\sigma^2}\right]}{1 + \exp\left[-\frac{b^2}{2\sigma^2}\right]}$$

Figure 3. The Superposition of Adjacent Gaussian Point Spread Functions.

Using the half intensity line widths specified in Appendix A for the F-15, F-16 and F-18 CRT displays, Equation 8 allows their standard deviations to be calculated. Table 1 gives the spot sizes and standard deviations for these CRTs.

TABLE 1

Aircraft CRT Spot Size/Standard Deviations

Aircraft Displays	Half Intensity Spot Diameter in Mils (.001")	Standard Deviation σ in Mils
F-15 VSD Display (3.8"x3.8")	10 15*	4.25 6.37*
F-16 Radar/EO Display (4"x4")	6-7 8.5-10*	2.55-2.97 3.61-4.25*
F-18 Multipurpose Displays (5"x5")	8 10*	3.40 4.25*

*Spot size maximum during high intensity operation of the CRT.

Since the stroke width of an ideal character varies as a function of the height selected for it, and the CRT line width remains fixed as character height is varied, there is no constant multiplicative relationship between the CRT difference luminance, ΔL, and the equivalent perceived luminance, ΔL_p. Comparisons therefore have to be made for each character size of interest, on each CRT display (i.e., of different spot size) for which a comparison is desired.

Table 2 shows calculated values of perceived difference luminance for alphanumeric characters used on the F-15, F-16 and F-18 CRT displays under 10,000 fc viewing/drive conditions. Matching or exceeding these perceived difference luminance values with dot-matrix displays characters used in like information display formats is necessary

TABLE 2

Perceived Luminance Values for CRT Alphanumerics
Under Maximum Specified Ambient Illumination Conditions

Aircraft Displays	Alphanumeric Character Height, h_c, (inches) /h (inches)	Character Difference Luminance, ΔL, in 10,000 fc Ambient	Perceived Difference Luminance, ΔL_p, in 10,000 fc Ambient
F-15 VSD Display	0.135/0.161 cd = 0.042	$\Delta L = 4L_D$	$\Delta L_p = 2.52L_D$
F-16 Radar/EO Display	0.149/0.165 cd = 0.059	$\Delta L = 4.6L_D$ $SW/SW_I = .60$ $\Delta L_p^*/\Delta L_p = 1.04$	$\Delta L_p = 1.72L_D$ $\Delta L_p^* = 1.79L_D$
F-18 Multipurpose Displays	1. 0.098/0.115 cd = 0.032	$\Delta L = 4.6L_D$	$\Delta L_p = 2.71L_D$
	2. 0.117/0.134 cd = 0.042		$\Delta L_p = 2.35L_D$
	3. 0.146/0.163 cd = 0.056	$SW/SW_I = .66$ $\Delta L_p^*/\Delta L_p = 1.02$	$\Delta L_p = 1.89L_D$ $\Delta L_p^* = 1.92L_D$
	4. 0.195/0.212 cd = 0.081	$SW/SW_I = .49$ $\Delta L_p^*/\Delta L_p = 1.10$	$\Delta L_p = 1.42L_D$ $\Delta L_p^* = 1.56L_D$
	5† 0.244/0.261 cd = 0.105	$SW/SW_I = .39$ $\Delta L_p^*/\Delta L_p = 1.17$	$\Delta L_p = 1.14L_D$ $\Delta L_p^* = 1.34L_D$

+Numeric Only

to allow substituting dot-matrix displays for their CRT display counterpart. An example calculation of the perceived luminance difference for the 0.135 inch high F-15 VSD alphanumeric character set is given in Appendix B. In addition, data for the other aircraft displays, and the conditions that must be satisfied to allow exact legibility equivalence to be achieved for ideal characters is described. Perceived luminance values following compensation for a difference in critical detail dimension between the CRT and ideal character dimensions has been starred in Table 2. The correction results in an increase in the luminance requirement to compensate for the decrease in critical detail dimension associated with the ideal character's wider stroke width dimension. The stroke width ratio and the luminance correction factor applied is shown in the second column where a correction was necessary. The corrections are based on experimental data for uniform luminance continuous stroke characters satisfying the compensation algorithm

$$\frac{\Delta L_p^*}{\Delta L_p} = \frac{.79X + .15}{X}, \quad .25 \leqq X \leqq .73 \qquad (9)$$

$$= 1 \qquad .73 < X \leqq 1.33$$

where

$$X = \frac{SW}{SW_I} = \frac{A}{A_e} \qquad (10)$$

3.3 Conclusions/Discussion of Results

Referring to Table 2 it should be noted that the smallest character, the 0.098 inch high F-18 alphanumeric set, has the highest perceived luminance requirement, $\Delta L_p = 2.71 L_D$. Moreover, as the size of the character sets increase the perceived luminance values drop, a result of the fixed stroke width of the CRTs used to depict the alphanumeric characters.

Since pilots consider each of the displays to be legible we may conclude that the perceived luminance relationship in the last column of Table 2 yields a legible alphanumeric character set given the set has as a minimum the critical detail dimension specified in column 1. Being able to match or exceed all of these perceived luminance levels with a dot-matrix display depicting the same character sizes under a 10,000 fL integrating sphere test condition assures such a display would be at least as legible as the aircraft CRT displays listed in Table 2.

The question of whether most or all of the perceived luminance requirements are excessive cannot be answered with certainty, however, we can be relatively certain the F-15, F-16 and at least one character size in the F-18 character set are probably very near to the required at-a-glance legibility limit. Comparing the critical detail dimension of the F-15 character set with that of the F-18, the 0.117 inch F-18 characters are seen to have the same critical detail dimension; therefore $\Delta L_p = 2.35 L_D$ should suffice to make this character size legible. The F-16 characters have a cd = 0.059 inches which falls between the F-18 0.146 inch high (cd = 0.056 inch) and 0.195 inch high (cd = 0.081 inch) alphanumeric character sets. The F-16 characters' perceived luminance requirement $\Delta L_p = 1.79 L_D$ also falls between the respective $\Delta L_p = 1.92 L_D$ and $\Delta L = 1.56 L_D$ requirements of the F-18 characters, and are therefore compatible requirements. We may conclude that the F-18 alphanumeric sets may be used as the basis for minimum perceived luminance values capable of assuring alphanumerics as legible as those depicted on aircraft CRTs.

Before a single value of perceived luminance can be selected from those available to be used as a design criteria, the minimum size alphanumeric character to be portrayed on the display must be known or alternatively it must be arbitrarily decided that the display shall be capable of producing as a minimum the perceived difference luminance required to make the smallest aircraft CRT alphanumeric character set in use legible. When assessing the desired sizes of alphanumeric characters it should be born in mind that CRT character heights are specified in terms of h_c rather than h, the visual height of the character (i.e., see Figure 1). Column 1 of Table 2 gives the visual heights, h, corresponding to the specified heights, h_c, for the CRT alphanumeric characters listed there. Continuous stroke and dot-matrix display characters are specified in terms of their visual heights. As may be seen from the comparisons in Table 2, the two variations of the same character height specification can lead to quite different impressions of the character's size.

SECTION 4

OVERVIEW OF PERCEIVED LUMINANCE REQUIREMENTS FOR GRAPHICS IMAGERY

4.1 Direct Sunlight Legibility Requirements

In the preceding section, perceived difference luminance values for legible aircraft CRT alphanumeric characters of different sizes were established. The resulting values have been plotted as a function of the character's critical detail dimensions on Figure 4. As a means of assessing the relative legibility of these character sets, Figure 4 also contains a plot of 95% accuracy threshold legibility data. This threshold data was selected to correspond to the 43.5 fL display background luminance, L_D, that is reflected by the F-18 multipurpose CRTs in a 10,000 fL diffuse surround luminance environment, and therefore matches the viewing condition applicable to the alphanumeric legibility data.

The ratio of the CRT derived perceived difference luminance values (i.e., that pilots have described as giving adequate display alphanumeric legibility) to the threshold legibility values increases linearly from 5.7 for the smallest (0.098" high) alphanumeric to 11.2 for the 0.244" high numeric character set. The constant legibility loci for the five F-18 alphanumeric characters occur at ratios above the 95% accuracy threshold of legibility of 5.73, 6.66, 7.59, 9.51 and 11.2 for alphanumeric sets having heights, h_c, of 0.098", 0.117", 0.146", 0.195" and 0.244" respectively. Thus in spite of the fact that the character stroke widths are fixed at 0.017" for all of these character sets, under the 10,000 fc drive condition, their legibility does improve as the height of the characters (i.e., and critical detail dimension) increases even though their perceived luminance levels decrease. Changes in legibility are desirable as a means of emphasizing the information presented with different height alphanumeric character sets.

By providing a minimum perceived difference luminance of $\Delta L = 2.71 L_D$, a display depicting the smallest alphanumeric character set used on the F-18 display can be made legible. Figure 4 can be used to determine the minimum perceived luminance requirement for other minimum character sizes.

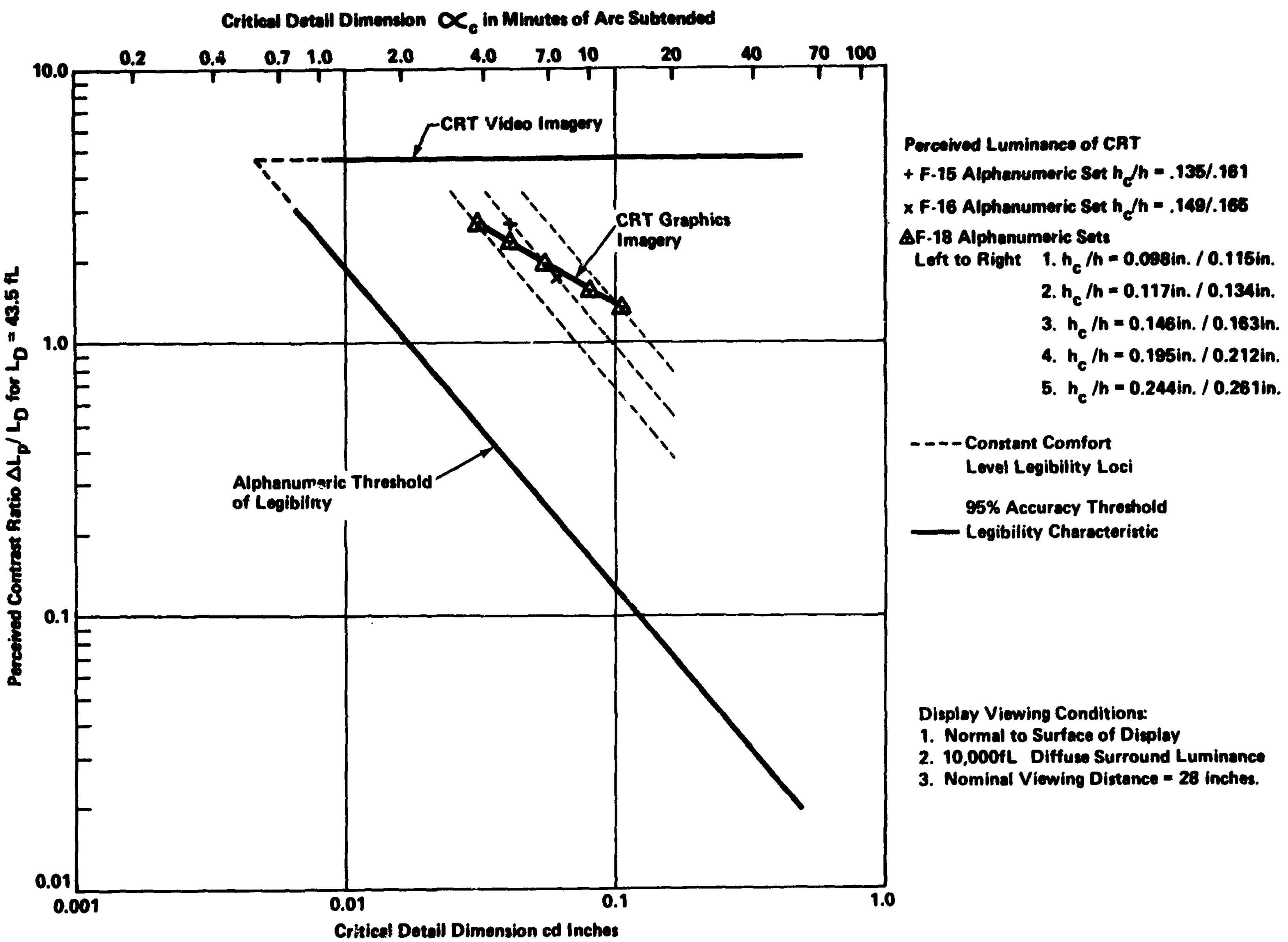


Figure 4. Relationship of Aircraft CRT Luminance Values to Human Perceived Luminance Requirements.

4.2 Legibility in the Presence of Glare

By providing a minimum perceived difference luminance of $\Delta L = 2.71 L_D$, in a 10,000 fL integrating sphere test environment, the smallest alphanumeric character set on the F-18 display can be made legible on any other type of display in either a 10,000 fL diffuse surround luminance environment or with a spot source of 10,000 fc illuminance incident on the display surface. Another source of instrument legibility degradation is exposure of the observer's eyes to glare sources such as the sun, the moon, flares, and lightning, for instance. Light from the glare source entering the eyes peripherally, while a display is being monitored foveally, is scattered in the eyes and as a result a portion of it is sensed by the foveal sensors being employed to view the display. The glare source induced scattered light is perceived as an increase in the background luminance level the display imagery is contrasted against and is referred to as veiling luminance, L_V. The name is derived from the visual perception that the scattered light emanates in the air volume between the eyes and the display being viewed creating the impression of a veil between the two. Quantitatively the effect produced is equivalent to adding the veiling luminance. L_V, to both the display symbol luminance, L_S, and to the background luminance, L_D, producing new symbol and background luminance levels L_S' and L_D' given by

$$L_S' = L_S + L_V \tag{11}$$

$$L_D' = L_D + L_V \tag{12}$$

The perceived difference luminance with veiling luminance present $\Delta L_p'$ is therefore given by

$$\Delta L_p' = L_S' - L_D' = L_S - L_D = \Delta L_p \tag{13}$$

which shows the perceived difference luminance is unaffected by the presence of the veiling luminance. Because the background luminance is affected the perceived contrast

$$C' = \frac{\Delta L_p'}{L_D'} = \frac{\Delta L_p}{L_D + L_V} \tag{14}$$

is reduced.

The veiling luminance effect occurs with equal impact on both light emitting and light reflecting head down displays and to both helmet mounted and head up displays as well. The magnitude of L_V increases as the glare source approaches the observer's line of sight and therefore is most severe on HUDs and HMDs where the glare source can coincide with the pilot's line of sight through a combiner. Head down displays can also be affected due to the fact that the initial background luminance of many of these displays is quite low thereby making even small values of veiling luminance potentially significant.

In recognition of this effect the recent F-16 and F-18 specifications have called for achieving a maximum difference luminance level, ΔL_{max}, in addition to the contrast requirement for sunlight legibility (i.e., see Appendix A). The maximum difference luminance specified for both aircraft was

$$\Delta L_{max} = L_{S\ max} - L_D \geqq 200 \text{ fL} \tag{15}$$

where $L_{S\ max}$ is the peak luminance of the stroke or raster written line and L_D is the display background luminance present during the measurement. The maximum perceived luminance associated with drawing CRT alphanumerics having 200 fL peak difference luminance lines may be calculated by substituting for ΔL in the $\Delta L_p/\Delta L$ ratios given in Appendix B, Table B-3. The result obtained is the same as would be obtained by substituting a display background luminance value of

$$L_V + L_D = L_D' = 43.5 \text{ fL} \tag{16}$$

for L_D into the $\Delta L_p/L_D$ ratios of Table 2. The need to see the least legible alphanumeric character set, means the smallest character that must be seen determines the perceived luminance level a display must be capable of meeting or exceeding. On the F-18 multipurpose displays, this is the 0.098 inch high alphanumeric character set which requires a perceived luminance satisfying

$$\Delta L_p \geqq 2.71\ L_D' \quad \text{where} \quad L_D' = 43.5 \text{ fL} \tag{17}$$

$$\Delta L_p \geqq 118 \text{ fL}$$

This perceived luminance is needed as a minimum to counteract the effects of veiling luminance to the same extent CRT displays are capable of doing so. If the minimum character size to be displayed is increased, then lower values of ΔL_p will suffice to match the CRT's capabilities. The CRT curve in Figure 4 can be used to determine the multiplication constant to replace 2.71 in Equation 17 once the critical detail dimension of the smallest character to be displayed is known.

4.3 Night Vision Legibility Requirements

Historically, painted, engraved, and transilluminated alphanumeric characters have been used on instruments, panels and controls. Based on the experience gained over many years of use, minimum acceptable dimensions for these characters have been developed. Referred to a nominal 28 inch viewing distance, minimum character heights are 0.15 inches for static characters used for legends, etc., and 0.2 inches for moving or time changing alphanumeric characters. Recommended stroke widths for these characters are between 1/8 and 1/7 of the character height (i.e., h in Figure 1). These characters therefore very nearly match the dimensions of the ideal characters previously described. Since the characters consist of white ≈ 87% reflectance paint or plastic contrasted with a 4% reflectance black background they have a directly measurable contrast (i.e., Appendix A, Equation A-1) of slightly greater than 20, or equivalently a perceived difference luminance of approximately $\Delta L_p = 20 L_D$, the numerical values being equal due to the nearly ideal dimensions of the characters.

In comparison with this, the smallest 0.115 inch high (*i.e.*, h_c = 0.098 inch) F-18 alphanumeric set is considered to be legible by pilots under worst case 10,000 fc atmospheric illumination conditions with a contrast of 4.6 as measured with a slit photometer or as a perceived difference luminance of only $\Delta L_p = 2.71 L_D$. Since the CRT derived perceived luminance requirement is considered acceptable by pilots, it may be correctly concluded that the requirement for large character sizes and high contrasts on conventional cockpit alphanumerics is not based on the high illuminance viewing condition, but rather on night viewing requirements.

Flight test data on instrument luminance level settings in conventionally equipped aircraft flown during night missions have shown that the luminance levels set by the crews depend on the type of mission being flown. Missions that can be flown IFR at night with external visibility restricted to airport takeoff and landing, and possibly navigation checkpoint verification during cruise; result in the cockpit lighting being set to provide between 0.1 and 1 fL of character difference luminance. In those missions where a strong requirement for external visibility is thought to exist, pilots attempt to optimize their dark adaptation both before and during a flight. In this case the minimum instrument lighting levels required to make critical information legible are used. The resulting average difference luminance levels under this night lighting condition is in the range of 0.04 to 0.09 fL. Smaller character sizes than those recommended as a minimum could be used for this viewing condition, however, the rapid degradation in visual acuity and the associated large compensating increases in character difference luminance levels needed to maintain information legibility mitigate against this design approach due to the degrading influence it would have on pilot dark adaptation.

The methods used to minimize the degrading effects on pilot dark adaptation associated with using small alphanumerics on the F-15, F-16 and F-18 CRT displays is not known to the author. The need to use sensor-video information during the night missions these aircraft fly would of course so severely degrade dark adaptation (i.e., due to the high luminance levels needed to make sensor video information legible at night) that small alphanumerics would not significantly add to the problem. All of the aircraft CRTs described in this report function extensively and in some cases exclusively as graphics overlayed sensor-video displays where the high night luminance level settings that are needed to perceive small alphanumerics are already necessary for the pilot to make effective use of the video information. If for instance 0.05 fL is needed to make the first grey shade legible, then the eighth $\sqrt{2}$ grey shade would be at a difference luminance, ΔL, of 0.52 fL. In practice this represents very nearly a minimum useful luminance setting to acquire video information at night. The associated alphanumeric luminance levels which are tied to the video luminance levels (i.e., see Appendix A) would be adequate to make small alphanumerics legible.

In the event night vision goggles are to be used, then it is necessary to be able to dim the instrument luminance levels to 0.02 fL or less.*

4.4 Perceived Luminance Control Requirements

The need for at least one and in many cases two knobs to control the legibility of each: multipurpose display, mission management display, and multifunction keyboard display, used in the cockpit and in addition to control displays containing one or more discrete readouts, the HUD and any of the conventionally illuminated electromechanical instruments, signal indicator and lighted panels already present in the cockpit, poses a potentially very high crew workload situation. Unlike conventional instruments and panels which use standard incandescent bulbs to permit ganged lighting control of whole instrument panels, each electronic display requires separate controls due to its individual legibility/control characteristics. Another difference is

*Different requirements apply for Generation III night vision goggles, since for these the cockpit displays are to be viewed by looking under rather than through the goggles.

that most electronic display techniques require some form of legibility control in response to changing ambient illumination condition during daylight operations, whereas the fixed contrast of conventional cockpit instruments make control of their legibility unnecessary, except at night.

To reduce the legibility control problems associated with electronic displays, each display should be equipped with an illuminance sensor and automatic luminance control circuitry. Individual trim controls to allow the pilot to initially set the legibility of his displays to meet his personal preferences would still be necessary, however, with the proper luminance control algorithms, the need to adjust an instrument after it is initially set would be minimized. Control adjustments could be totally eliminated if automatic adaptation control could also be implemented through the sensing of pilot visual exposure to glare sources and with the instrument perceived luminance recovery time constants controlled to match visual adaptation time constants.

Curve #1 in Figure 5 represents an approximately constant comfort level of legibility as the reflected luminance L_D varies in response to exposure of the display to illuminance levels from 10^{-6} to 10^{+4} fc. Curve #1 gives a contrast ratio $C = \Delta L_p/L_{DS} = 3$ at a display background luminance $L_{DS} = 43.5$ fL slightly higher than the 2.7 normal viewing contrast determined for the smallest alphanumeric character set used on the F-18 CRT displays. Curve #2 in Figure 5 gives a minimum perceived luminance requirement corresponding to viewing the display at an angle of 45° from the surface normal. This curve gives a contrast ratio requirement of $C = \Delta L_p/L_{DS} = 2$ for $L_{DS} = 43.5$ fL.

The increase in the contrast ratio requirement to $C = 3$ from 2.71 is in recognition of the fact that many locations for displays in aircraft cockpits cause them to be viewed at angles greater than the approximately 20° maximum viewing angle applicable to the F-15, F-16 and F-18 CRT installations. Assuming a Lambertian emission surface with a $\cos \theta$ difference luminance angular dependence, a display with a contrast ratio of $C = 3$ at $\theta = 0^\circ$ would have a contrast ratio of $C = 2.6$ at $\theta = 30^\circ$ which would produce a contrast still in excess of the $C(\theta=0^\circ) =$ 2.71 contrast if viewed at an angle of 20°. In practice, primary instrument locations seldom result in viewing angles greater than 30°.

The upper bound of the required control region of Figure 5 corresponds to the approximate onset of image bloom caused by light dispersion within the human's eyes becoming visible due to the high symbol to background contrast. Within the required luminance control

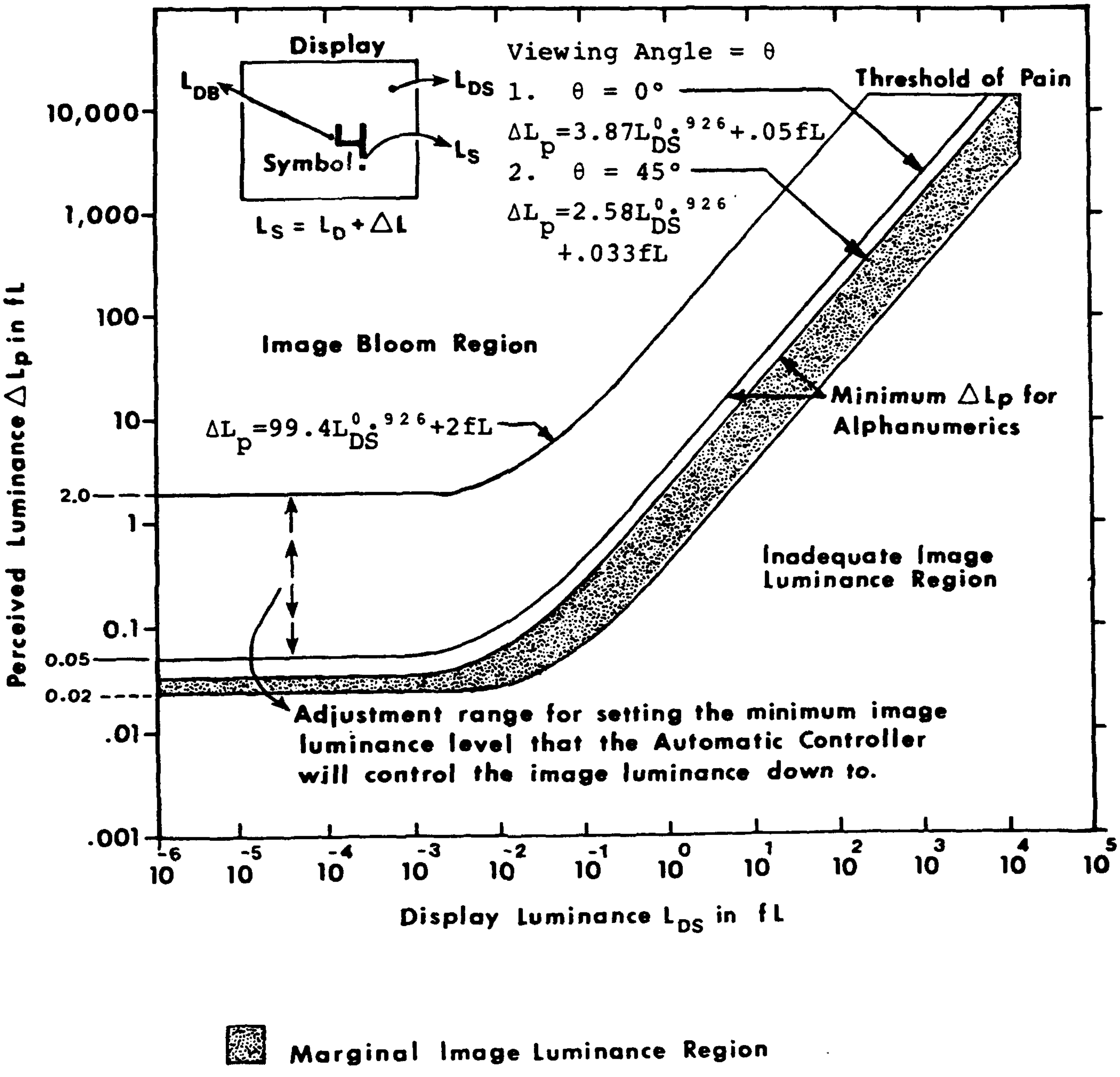


Figure 5. Perceived Luminance Control Requirements

region, curves of approximately equal legibility satisfy the control algorithm

$$\Delta L_p(L_{DS}) = \Delta L_{pc} + (1.42 + 49\Delta L_{pc})L_{DS}^{0.926} fL \qquad (18)$$

where increasing ΔL_{pc} values in the range (i.e., see ordinate axis intersections of the $\Delta L_p(L_{DS})$ characteristic in Figure 5)

$$0.05\ fL \leqq \Delta L_{pc} \leqq 2\ fL \qquad (19)$$

produce increasingly higher levels of aircrew viewing comfort.

The lower L_{DS} limiting values of ΔL_p determined by Equation 18 are lower than constant legibility over the entire illuminance control range would demand. This was done in recognition of pilot preferences to make do with less than comfort level legibility in the interest attaining good dark adaptation. An ability to internally adjust the lower ΔL_p limiting values should be incorporated.

Manual trim adjustment of ΔL_{pc} values, at least over the range of 0.05 fL to 2 fL, should be possible and excursions outside of this range would be permissible. Control down to at least 0.02 fL to permit the use of night vision goggles should be achieved.*

In addition to the manual trim adjustment knob a fully manual luminance override control should be incorporated to allow instrument operation from minimum to full luminance under any illuminance viewing condition. This control option should be selectable by rotating the manual trim adjustment knob of the automatic luminance control (ALC) circuitry to a maximum luminance detent position. The instrument could be turned off using a zero luminance detent position on the manual luminance override control knob.

4.5 Optical and Electrical Crosstalk

The breakup of the display background luminance, L_D, in Figure 5 into L_{DB} and L_{DS} terms is for the purpose of specifying optical crosstalk from activated to unactivated pixels. The lack of a sharp spatial luminance transitions from the perceived image luminance to the "off" display background luminance level, L_{DS}, is perceived as image blur. The optical crosstalk difference luminance, ΔL_{OC}, between "on" and "off" pixels should satisfy the following criteria

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*A decrease below 0.05 fL is not required if Gen III night vision goggles are to be used.

$$\Delta L_{OC} = L_{DB} - L_{DS} \leqq 0.05\ \Delta L_p \tag{20}$$

where L_{DB} is the background luminance in the area immediately surrounding an activated pixel (i.e., measured at an adjacent pixel location in a dot-matrix display).

A display can be considered to exhibit electrical crosstalk when difference luminance levels on unactivated areas of a display's surface are visually perceptible. The electrical crosstalk difference luminance, ΔL_{EC}, of unintentionally activated pixels should at a minimum satisfy the following criteria

$$\Delta L_{EC} \leqq 0.02\ \Delta L_p \tag{21}$$

In both of the foregoing criteria ΔL_p is the maximum perceived luminance depicted on the display. The criteria should be satisfied over the entire perceived luminance ΔL_p operating range of the display. The crosstalk criteria specified by Equations 20 and 21 do not entirely eliminate the ability to perceive the effects on a display when it is closely examined. Satisfying the criteria does assure the effects will not be noticeable to a person using the display and moreover will not degrade his performance while using the display.

SECTION 5

LUMINANCE REQUIREMENTS FOR GRAPHICS DEPICTED ON DOT-MATRIX DISPLAYS

The perceived luminance, ΔL_p, of the dot-matrix display character like that of the continuous uniform luminance profile stroke character and the CRT Gaussian luminance profile character, can be calculated using Equation 3 (i.e., luminance averaging). The dimensions of two dot-matrix alphanumeric character fonts are illustrated in Figure 6. In the event the activated dot-matrix pixels are visually discrete, having a negligible difference luminance, $\Delta L(x,y)$, contribution in the areas surrounding the activated pixels, then Equation 3 may be written in the simplified algebraic form

$$\Delta L_p = \frac{A_d}{A_e} \Delta L \tag{22}$$

where A_d is the area of the activated pixels or dots of average luminance, ΔL, within the per unit effective area of the character, A_e, selected for luminance averaging. The minimum unit effective area is given by the Area, A_e, for a dual dot stroke width character

$$A_e = d_s \frac{SW_I}{2} \quad \text{(dual dot stroke width)} \tag{23}$$

the dimension, d_s, being the periodic center to center spacing of the pixels used to form the character. The minimum unit effective area for a single dot stroke width character is given by

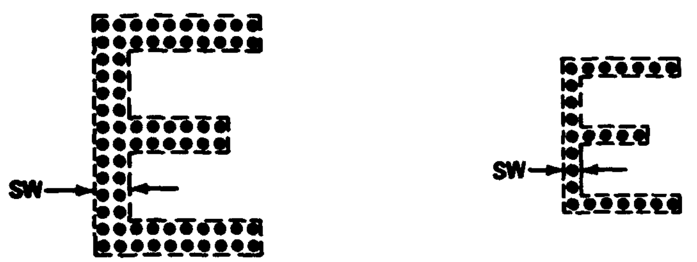
$$A_e = d_s\, SW_I \quad \text{(single dot stroke width)} \tag{24}$$

In general the minimum unit effective area is given by

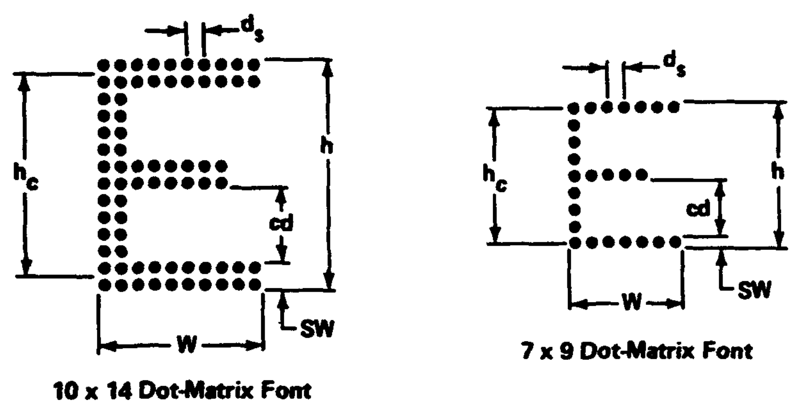
$$A_e = d_s\, SW_I/n \tag{25}$$

where n is the number of dots forming the character stroke width.

To match or exceed the CRT derived perceived luminance requirements of the last section it is necessary for the mean luminance of a dot-matrix display pixel to satisfy the equation



a. Luminance Averaging Area Shown Bounded by Dashed Lines One Stroke Width (SW) Apart (Illustrated for SW = 0.12h)



b. Character Dimensions for Two of the Potential ASCII Character Fonts.

Figure 6. Geometric Relationships for Characters to be Depicted on DOT-Matrix Displays.

$$\Delta L \geq \frac{A_e}{A_d} \Delta L_p \tag{26}$$

where the difference luminance requirement is seen to depend on the effective area to dot area ratio of the particular dot-matrix display design, and the perceived luminance requirement, ΔL_p, depends on the critical detail dimension of the ideal uniform luminance character to which it applies.

Using 10x14 dual dot stroke width characters, Equation 22 has been experimentally found to apply for area ratios down to $A_d/A_e = 0.2$. The use of the dual dot stroke width character permits the reduction in the dot to effective area ratio while still maintaining a dot character to ideal character stroke width ratio of $SW/SW_I > .73$ needed to avoid correcting for critical detail dimension differences between dot-matrix and ideal characters of the same height, h_c. Failure to correct for the increased critical detail dimension of narrow stroke width dot-matrix characters through the use of Equation 26 to predict the required dot difference luminance, can at worst result in a slightly excessive value of ΔL. It should be noted that while the dot area ratios were only tested down to $A_d/A_e = 0.2$, other types of visual perception tests would indicate that Equations 3, 22 and 26 should remain valid independent of how small the dot area is made.

In practice the noise difference luminance, ΔL_N, between activated pixels on dot-matrix displays is seldom negligible. Moreover, because the "off" area, $A_e - A_d$, can, for small pixels, be large in comparison to A_d, even small noise luminance levels can have a significant effect on the perceived luminance. When noise luminance is not negligible, Equation 3 can be integrated by parts to yield

$$\Delta L_p = \frac{A_d}{A_e} \Delta L + \frac{A_e - A_d}{A_e} \Delta L_N \tag{27}$$

where ΔL_N is the average luminance in the unactivated portion of the area A_e. In a character such as the 10x14 dot-matrix letter E in Figure 6, ΔL_N represents the superposition of optically coupled luminance from both the pixel itself and the adjacent activated pixels. Thus a display having coupling to adjacent unactivated elements of about 5% (i.e., insufficient to cause the character edges to appear blurred) could cause a ΔL_N within the character boundaries of greater than 20% of ΔL. For a pixel area ratio of 0.2 the noise and pixel luminance contributions to the perceived luminance, ΔL_p, could therefore be nearly equal.

As a final comment on Equation 22, it should be pointed out that this expression is not completely equivalent to the percent active area relationship that has come into common useage in the literature. If an area, A_a, given by

$$A_a = d_s^2 \tag{28}$$

is defined and substituted for A_e in Equation 22, the result is percent active area compensation of dot luminance. The error involved in using percent active area rather than the dot to effective area ratio is small as long as the dot spacing, d_s, satisfies the equation

$$d_s \cong SW_I/n \cong h_c/7n \tag{29}$$

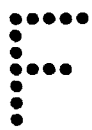
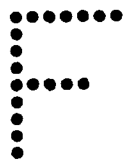
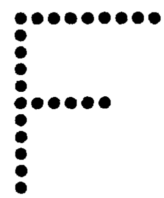
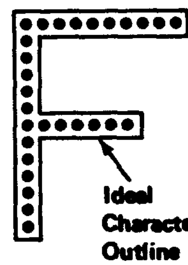
where SW_I is the ideal character stroke width, n is the number of dots forming the dot-matrix character stroke width, and h_c is the dot-matrix character height, as illustrated in Figure 6.

Increasing a dot-matrix character's size through the expansion of the dot-matrix font size X x Y without a proportionate increase in the dot stroke width produces a situation where the percent active area relationship fails to correctly predict the required dot difference luminance levels, ΔL, for legibility equal to that of an ideal character. This is illustrated in Table 3 where the active area difference luminance requirement prediction is more than a factor of two lower than it is for the effective area technique. The test characters originally used to establish the active area luminance compensation technique, satisfied the equivalence requirement of Equation 29. As a result, the technique predicted correct results in that instance. A considerable advantage of the percent active area criterion is that it is specified entirely in terms of the display pixel dimensions and spacings, and is therefore an invariant characteristic of a particular display design, rather than being dependent on the form of the information being displayed. The percent active area criteria still remains a good approximate predictor of character legibility in many instances.

Before concluding this discussion it should be noted that the selection of a minimum character height to be depicted on a dot-matrix display not only determines the maximum perceived luminance the display must be capable of producing but also determines the minimum pixel density that must be employed to depict it. Numerous independent tests on static upright dot-matrix characters have shown that optimum character identification performance requires a minimum dot-matrix font size of 7x9 dots. The same tests demonstrate that further increases in the dot-matrix font size cause no improvement or degradation in performance assuming the same perceived luminance is achieved in all cases. The poorer performance achieved with 5x7 or smaller character fonts does not result from legibility differences but is rather due to an increase in character recognition errors. For these reasons the minimum size dot matrix font used on aircraft displays should by 7x9.

TABLE 3

Comparison of Active and Effective Areas

Dot-Matrix Character				
X x Y	5 x 7	7 x 9	9 x 11	10 x 13
Active Area $\frac{\Delta L}{\Delta L_p} \geqq \frac{A_a}{A_d} =$ **Example:** If $A_d = d_d^2$ $d_d = 0.5 d_s$ $\frac{\Delta L}{\Delta L_p} \geqq$	$\frac{d_s^2}{A_d}$ 4	$\frac{d_s^2}{A_d}$ 4	$\frac{d_s^2}{A_d}$ 4	$\frac{d_s^2}{A_d}$ 4
Effective Area* $\frac{\Delta L}{\Delta L_p} \geqq \frac{A_e}{A_d} =$ **Example:** If $A_d = d_d^2$ $d_d = 0.5 d_s$ $\frac{\Delta L}{\Delta L_p} \geqq$	$\frac{1.06\, d_s^2}{A_d}$ 4.24	$\frac{1.41\, d_s^2}{A_d}$ 5.64	$\frac{1.77\, d_s^2}{A_d}$ 7.08	$\frac{2.12\, d_s^2}{A_d}$ 8.48

*$A_e = SW_l d_s$; $SW_l = 0.176 h_c = 0.176\,(Y-1) d_s$ $\therefore A_e = 0.176\,(Y-1) d_s^2$

Table 4 illustrates the minimum dot-matrix display resolutions necessary to depict 7x9 alphanumeric characters of various heights. Once a resolution is selected then characters of greater than the minimum height can be formed using larger dot-matrix font sizes. As the dot-matrix font size is increased the number of dots making up the character stroke width can be increased to give improved legibility.

TABLE 4

Minimum Resolution Required to Depict
7x9 Characters as a Function of Their Height

Character Height hc	Dot Spacing ds	Minimum Resolution r(dot/inch)
.100	.0125	80.0
.120	.0150	66.7
.128	.0160	62.5
.144	.0180	55.6
.160	.0200	50.0
.176	.0220	45.5
.200	.0250	40.0
.240	.0300	33.3
.272	.0340	29.4
.320	.0400	25.0
.400	.0500	20.0

SECTION 6

VIDEO DISPLAY IMAGE LEGIBILITY REQUIREMENTS

6.1 Introduction

In the preceding sections complex graphics characters, as typified by alphanumerics, were analyzed to determine the relationship between the difference luminances, ΔL, produced by different types of displays and the resulting perceived difference luminance, ΔL_p, that is effective in predicting operator performance using the display. The luminance averaging equation, Equation 3, was used as the basis for establishing the luminance relationships. The basis for video image perception assessment is not as clear cut as it is for graphics and the implications of the known human perceptual characteristics on dot-matrix video display design requirements is not at this time predictable with a high level of confidence in the results.

The human perceptual characteristics known to be operative when viewing video display imagery take on two different forms depending on the type of information being acquired from the display. The goal of viewing sensor video information for the purpose of target detection, target recognition or target identification is to achieve these objectives at the largest possible aircraft to target ranges. The size of the displayed target image at detection and of the critical detail dimensions required to permit recognition and then identification to occur are very small, involving only a few picture elements. Because the critical target dimensions are so small, the crew members' full attention and maximum visual acuity capabilities are focused on the target imagery.

Test results show that under these conditions, dot-matrix display pixels are perceived at their actual measurable difference luminance levels with no perceived luminance averaging. This result has been shown to be valid for pixel percent active areas between 20% and 100%, as long as the pixel dimensions do not drop below about 0.7 minutes of visual arc (i.e., about 5.6 mils at a 28 inch viewing distance). Below 0.7 arc-minutes the spatially averaged luminance of a 0.7 arc-minute dot is perceived. Conversely when the goal of viewing sensor video information is to acquire situation information, that is where small image details are not being focused on, then the display scene is perceived as the spatially averaged difference luminance given by

Equation 3, just as it is for graphics information portrayals. The contradictory effect that these two very different video perception characteristics have on dot-matrix display video image rendition requirements is not encountered on aircraft CRT displays.

6.2 Spatial Luminance Distributions of CRT Depicted Video Imagery

To be able to match or exceed the legibility of an aircraft CRT display, a dot-matrix would as a worst case requirement have to provide perceived luminance and contrast equal to that possible with a CRT display. To make this comparison the spatial luminance distribution resulting from the portrayal of video information on raster written CRT displays must be known. An approximate technique for assessing this spatial luminance distribution is to calculate the relative modulation resulting when a constant spatial luminance object scene is depicted on the CRT display.

6.2.1 Perceived Luminance of CRT Video Imagery

Referring to Figure 3, which shows the relative modulation of two adjacent raster (i.e., Gaussian approximation) lines as a function of their spacing, b, and using the 480 line, 120 line/inch vertical resolution of the F-16 4"x4" CRT display as an example, the relative modulation may be calculated as $M = 0.35$ for $b = 8.33$ mils and $\sigma = 2.76$ mils (i.e., corresponding to a mean spot diameter of 6.5 mils). The equivalent room ambient beam drive modulations for the F-15 and F-18 CRT displays at 120 lines/inch resolution (i.e., $b = 8.33$ mils) are $M = -0.172$ and $M = 0.053$ respectively.

The negative modulation calculated for the F-15 CRT indicates that at 120 lines/inch resolution, the luminance between lines is greater than at the center of the lines, showing as its specifications indicate (i.e., see Appendix A) that the F-15 CRT is not designed for use at the 120 line/inch resolution. The 35% modulation of the F-16 and 5.3% of the F-18 convert to valley luminances of 65% and 94.7% of their peak line luminances, respectively.

The point of this discussion is that there would normally be very little difference between the peak luminance of a single CRT line and the spatial average of its video image luminance integrated over both bright and dark line areas. This means the perceived luminance and contrast of CRT depicted imagery calculated using Equation 3 is approximately equal to the measured values of luminance and contrast and that the values used to specify CRT displays in Appendix A need not be altered to serve as a basis for establishing dot-matrix display luminance requirements.

6.2.2 Spatial Factors Influencing CRT Image Quality

There are a number of spatial factors that influence the image quality possible on an aircraft CRTs which either do not have comparable problems on dot-matrix displays or the magnitude of the effect can be made so low it would not be considered a problem on the dot-matrix display. The image quality factors that are in this category include: (1) display image jitter, (2) display dimensional stability, (3) display positional stability, (4) linearity, (5) image blur and (6) false images.

Display image jitter is the movement of the display imagery with respect to the display surface between successive refresh times when the imagery is supposed to be static. The F-18 multipurpose CRT specification requires that jitter not exceed 0.010 inch (i.e., slightly greater than its half intensity spot diameter of 8 mils) under maximum vibration conditions.

The display dimensional stability refers to changes in the displays active area screen size (i.e., its active raster addressed area). The specifications for the F-18 CRTs require that the total active area not change by more than 2% in any direction in any mode of operation, during mode switching or during aircraft power variations.

The F-18 CRT display positional stability specification requires that position changes "of any display data will not exceed $\pm$ 0.008 inches vertically and/or horizontally during and/or after exposure to any combination of environments."

The linearity specifications of the F-18 CRT displays require that "the linearity of the deflection factor (electrical input units/inch of deflection) will be within $\pm$ 2% from the center of the display to 80% of the distance to the edge of the useable display surface in all directions. Beyond 80%, the linearity may be degraded to $\pm$ 5%."

Due to the dimensional invariance of dot-matrix display surfaces, the above four CRT image quality factors have no parallel factors on direct view dot-matrix displays. There would be parallel image quality factors in optically projected dot-matrix displays, however, and in that case the foregoing CRT specifications would have to apply to projection dot-matrix display as well.

Image blur or alternatively crosstalk between pixels is not specified directly on CRT displays, rather the relative modulation that must be achieved at a specified number of lines or line pairs per inch in response to a square wave signal is specified (i.e., see

Appendix A). In spite of this it is still of interest to assess the coupling that occurs from an "on" CRT line area to an "off" CRT line area, just as is done for "on" to adjacent "off" pixels on dot-matrix displays.

Table ives as a percentage the relationship between the integrated rage difference luminance, ΔL_c, coupled to the adjacent "off" CRT line area from an "on" line of integrated average difference luminance, ΔL_L. The CRT line was assumed to have the Gaussian luminance distribution of Figure 2, with standard deviations corresponding to the F-15, F-16, and F-18 CRT displays under both room ambient and 10,000 fc ambient drive conditions. Since all of these displays have slightly different resolution specifications, for purposes of comparison a resolution of 125 lines per inch or a line spacing of 8 mils was arbitrarily chosen to correspond to a one minute of arc line spacing at a 27.5 inch viewing distance. The average line difference luminance, ΔL_L, was calculated by taking L(X) contributions between -4 mils and +4 mils with the center of the line at the origin. The coupled difference luminance was calculated by integrating L(X) values from +4 mils to 12 mils.

The existence of luminance coupling in perceptible amounts, $\Delta L_c/\Delta L > 5\%$ means that image blur is present to some degree. Experience with alphanumeric characters shows that the presence of blur can be compensated for by increasing the character's difference luminance. This raises the question of whether CRT video luminance requirements could be elevated by the presence of blur.

In addition to producing blur the existence of coupling between picture elements makes it impossible to exactly reproduce an object scene. Moreover as was indicated by the relative modulation calculation for the F-15 display under room ambient drive conditions, closely spaced CRT lines can result in superimposed luminance levels between raster lines greater than either of the signal (line) luminances responsible for them. This effect is aggravated under the 10,000 fc CRT drive condition. It in essence results in false images and represents a form of image noise generated by the display, due to the coupling between adjacent or near neighbor activated CRT lines. Although the coupling effects are not as easily described in the horizontal scan direction, and their outward effects differ slightly from the vertical inter-line effects, their presence nonetheless has a degrading influence on the image quality of CRT video presentations.

In general, while optical and in some cases electrical coupling may be present on dot-matrix displays, judicious design can keep the level of coupling present well below the 5% or greater levels required for perception of blur to occur. Due to the reduced levels of coupling

TABLE 5

CRT Inter-Line Luminance Coupling*

Aircraft	Illumination Ambient	Standard Deviation in mils	Coupling Ratio L_c/L_L in %
F-15	Room	4.25	26.2
	10,000 fc	6.37	50.0
F-16	Room	2.76	8.6
	10,000 fc	3.93	22.2
F-18	Room	3.40	15.7
	10,000 fc	4.25	26.2

*Calculated results assuming Gaussian lines drawn on 8 mil centers present on dot-matrix display it can be concluded that false image (i.e., display induced noise) effects would be reduced in comparison to CRT displays. Overall it must be concluded that spatial factors that influence the image quality performance of a CRT have little or no effect on the image quality of dot-matrix displays.

6.3 Dot-Matrix/CRT Display Image Quality Comparison for Matched Average Luminance Displays

As previously indicated, one approach that is certain to cause the legibility performance of dot-matrix video displays to match or exceed the performance of CRT video displays is to select dot difference luminance values so that, at the same background luminance level, the spatially averaged difference luminance of the dot-matrix display equals the spatially averaged luminance of the CRT display. In other words the application of Equation 3 to both the dot-matrix display and the CRT display should yield the same perceived luminance/contrast values.

Since the average pixel difference luminance for a 20% active area dot-matrix display could be as much as five times as much as its average perceived luminance (i.e., for video situation data), this approach could at worst cause the small critical detail dimensions associated with image detection, recognition and identification to be perceived at five times the difference luminance values of comparable imagery depicted on a CRT display. The impact of this difference on video image legibility will now be considered.

In assessing a scene to be depicted on a CRT display it has been shown that areas of uniform luminance in the scene will transfer to the display as areas of approximately uniform luminance. Based on modulation transfer function (MTF) characterizations of a CRT or more precisely based on the CRTs sine wave response (SWR), higher spatial frequency components in a scene are progressively more attenuated as the spatial frequency required to depict smaller and smaller critical detail dimension imagery present in the scene increases. The CRT therefore provides a degraded high spatial frequency rendition of the actual scene (i.e., small imagery is blurred).

The spatial frequency response function for dot-matrix displays does not degrade as spatial frequency is increased, rather it remains approximately constant out to the limiting spatial frequency that can be represented on it. This limiting spatial frequency corresponds to the display's pixel density. As a result of the flat spatial response characteristic, small imagery remains sharply defined (unblurred) on dot-matrix displays and retains the high difference luminance/contrast present in the sensed object scene.

Unlike the continuous spatial frequency transfer function that is applicable to the CRT's horizontal (i.e., continuous line) scan direction, the vertical direction on the CRT is characterized by fixed discrete spatial samples of the image scene, one for each raster line present. Like the vertical direction on the CRT, dot-matrix displays also provide a discrete spatially sampled rendition of the object scene sensed, however, in this case sampling occurs in both the horizontal and vertical directions.

The Nyquist Sampling Theorem applied to the spatial frequency domain requires that spatial sampling occur at a sampling frequency of at least twice the highest spatial frequency of interest in the object scene being displayed, in order for the object scene to be depicted with complete authenticity on the display. Thus a dot-matrix display having 125 pixels per inch resolution can render a display image of an object scene that has the equivalent of a maximum spatial frequency content of up to 62.5 cycles per inch with complete authenticity. Object scenes having spatial frequency content beyond the 62.5 cycles/inch authenticity limit of a dot-matrix display have their display images distorted. Misregistration of elements of the object scene with the discrete pixel locations of the display image scene (i.e., up to half a pixel position error) is one source of distortion. Another source of distortion results from the display pixel shape having no relationship to the object scene area it depicts.

The CRT display also has an image sampling authenticity limit related to its raster scan lines. Full object scene authenticity on a 125 line/inch CRT display cannot, however, be assured, for spatial frequencies of up to 62.5 cycles/inch in the display image scene, due to the previously discussed inter-line information overlap resulting from the spread of the Gaussian CRT spot. In the horizontal direction the spread of the CRT spot has the same effect, however, the continuous modulation of the CRT beam does provide correct local object/image registration in this direction.

In the context of actual aircraft missions, the critical spatial frequency of a target is directly related to the dimension of the critical details on the target that must be resolved to successively allow aircrew detection, recognition and identification to occur. As the range of the aircraft from the target decreases the angle the target's critical detail dimension subtends increases and concurrently its associated critical spatial frequency, expressed in cycles per unit angle subtended, decreases. Target detection, recognition and identification occur when the highest (critical) frequency present in the respective spatial frequency converted image spectrums, as depicted on a video display, become small enough to permit perception to occur. In other words the better the high spatial frequency rendition capability of a display is, the greater will be the aircraft's range when perception of the target occurs.

It can be concluded that providing the pilot with a dot-matrix display having a spatially averaged difference luminance equal to that of a CRT would assure equal perception of low spatial frequency video (i.e., situation) data. Moreover, the flat high spatial frequency response of the dot-matrix display in comparison to the progressively attenuated response of the CRT would provide the pilot with the potential for extended aircraft to target detection, recognition and identification ranges. Finally, if dot-matrix display active areas of less than 100% are used, with dot minimum dimensions not less than 0.7 arc minutes (i.e., 5.6 mils at a 28 inch viewing distance), then high spatial frequency emphasis of small critical detail dimension targets will occur during target detection, recognition and identification tasks. The emphasis of the high spatial frequency content of an object scene is predicated on the experimental result described earlier that the dot luminances are averaged for large critical detail dimension visual imagery (i.e., low spatial frequency content images) and are seen at full luminance when image critical detail dimensions consist of only a few pixels (i.e., high spatial frequency content images).

6.4 Overview of Legibility Requirements for Video Imagery Portrayed on Dot-Matrix Displays

In the event the average luminance matching technique is employed as the method for determining minimum dot-matrix display legibility requirements, then the following video image legibility requirements would have to be satisfied. The luminance values used in the requirements would be the perceived luminance values calculated from the actual dot luminances using Equation 3 with the effective area, A_e, used in the equation being equal to the area of a 100% active area pixel. The required difference luminance for a 20% active area pixel having no noise luminance in the "off" area surrounding it would therefore, for example, have to be five times the difference luminance of a CRT display of the same spatially averaged contrast.

6.4.1 Grey Scale

Each discrete, perceptible, total image luminance level, $L_s(n)$, either above or below an ambient illumination induced background luminance, L_D, in unenergized areas of a display, is considered a grey scale level, of grey shade index, n, where $L_s(n=1)$ is the background luminance level, L_D. In daylight (photopic) viewing conditions, equally perceptible grey scale Increments between progressively higher grey shade levels can be approximately achieved by satisfying the measured luminance criteria:

$$L_s(n) \stackrel{\Delta}{=} (GR)^{n-1} L_D(n=1), \; n=1,2,\ldots \tag{30}$$

where GR is the grey scale ratio.* In terms of the difference luminance of the display, ΔL_p (i.e., also the difference in luminance perceived by a human), the grey scale requirement for the nth grey shade becomes

$$\Delta L_p(1 \to n) = L_s(n) - L_D(n=1) = [(GR)^{n-1} - 1] \, L_D(n=1) \tag{31}$$

with respect to the background luminance level, $L_D(n=1)$, and

$$\Delta L_p(n-1 \to n) = L_s(n) - L_D(n-1) = [GR-1] L_D(n-1) \tag{32}$$

with respect to the next lower grey shade. This method of specifying grey scale results in equal contrast increments

$$C = \frac{\Delta L_p(n-1 \to n)}{L_D(n-1)} = GR-1 \tag{33}$$

between equally perceptible adjacent grey scale levels. The generally accepted minimum grey scale ratio is $GR = \sqrt{2}$. Grey scale multiplier values corresponding to different grey scale ratio increments are shown in Table 1. Increasing the grey scale ratio makes target detection, identification and recognition easier for an aircraft crew member, but also increases the dynamic luminance control range and maximum emitted luminance the display must be capable of producing.

TABLE 6

Contrast Between Adjacent Grey Shades

Grey Scale Ratio: GR	Grey Shade Contrast: C_{GR}	Grey Shade Multiplier GR^{n-1}, n=							
		2	3	4	5	6	7	8	9
$\sqrt{2}$ = 1.414	0.414	1.41	2	2.83	4	5.7	8	11.3	16
1.5	.5	1.5	2.25	3.38	5.06	7.6	11.4	17.1	25.6
1.63	.63	1.63	2.66	4.33	7.06	11.5	18.8	30.6	49.8

*Subsequent analysis has shown that the Munsell Value Scale provides a better approximation to equally perceptible grey shade steps.

Like the CRT, the dot-matrix video display grey scale ratio requirement should be controllable up to GR = $\sqrt{2}$ or greater. It should furthermore be maintained throughout the range of possible ambient illumination induced, L_D, values and throughout the entire grey scale range, n=1 to 8. Eight grey shades meeting the above requirements are necessary to produce video imagery perceived to be of high image quality. A control to permit varying the grey scale ratio either continuously or in increments at least up to GR = $\sqrt{2}$ and preferably higher should be provided.

6.4.2 Luminance/Contrast

Referring to Table 6, and Equation 31, the display image contrast required to provide eight grey shades at a minimum grey scale ratio of GR = $\sqrt{2}$ is

$$C_{Min}(n=8) = \frac{\Delta L(1\text{-}8)}{L_D(n=1)} = [(GR)^{n-1}-1] = 10.3 \tag{34}$$

Hence the display minimum emitted luminance requirement for a flight-worthy video display would be

$$\Delta L_{Min}(n=8) = 10.3 L_D(n=1) \tag{35}$$

where the value of the display background luminance L_D is determined by the composite reflectance of the display's optical system. Due to the effects of glare source induced veiling luminance in the human's eyes a minimum value of L_D=43.5 foot-Lamberts (fL) should be used to calculate minimun, ΔL, values. The minimum filtered display difference luminance needed to portray eight grey shade video imagery is therefore 448 fL. However, in line with the 6 grey shade legibility requirement of CRT displays, a minimum image luminance of $L_s = 5.67 L_D$ in 10,000 fc or ΔL = 200 fL whichever is higher is required.* These criteria shall be considered to apply to the mean luminance of the dot-matrix display imagery, and not to the luminance of individual pixels which can be higher.

6.4.3 Graphics Overlay of Video Imagery

The F-15 and F-18 CRT display specifications require that graphics overlayed on video have one higher grey shade of image luminance, or in a 10,000 fc diffuse surround illumination environment, a graphics image luminance, $L_s(n=7) = 8\ L_D(n=1)$ (i.e., $\Delta L_p=7\ L_D$). The F-16 radar/EO display requires a contrast ratio of $C=L_s/L_D=7$ under the same illumination environment.

*Subsequent analyses have resulted in lowering this requirement to the ΔL=160 fL specified in MIL-L-85762.

6.4.4 Luminance Uniformity

Luminance variations over the surface of a uniformly energized video display, represent a potential source of time invariant, spatially discriminable noise when mixed with an input video signal during the display of video imagery. The luminance ratio of positive and negative luminance value excursions, δL, about the mean grey scale luminance setting, $L_s(n)$, will be designated as U_L and defined as

$$U_L \stackrel{\Delta}{=} \frac{\delta L}{L_s(n)} \tag{36}$$

The quantity U_L defined here is a variable having a distribution of values dependent on the XY coordinate position of each point on the display surface that is characterized. The statistical quantities characterizing this spatial luminance distribution for the entire array and its spatial frequency domain counterpart, provide potentially useful measures of display luminance uniformity, however, such measures and their associated human performance criteria relationships have not yet been established. A method of placing an upper bound on the values the luminance uniformity variable, U_L, can assume, will be presented as an alternative to the statistical approach.

In a video display, a maximum luminance increment, δL_M, exists beyond which a picture element having a large U_L value would cause the signal grey scale level to be displayed in either the next higher or next lower video image grey scale range. The luminance increment, δL_M, is therefore the threshold of grey shade overlap. The luminance level corresponding to grey shade overlap, L_{GO}, between levels n and n+1 will satisfy the equation.

$$\begin{aligned} L_{GO}(n \leftrightarrow n+1) &= L_s(n) + \delta L_M(n) = L_s(n+1) - \delta L_M(n+1) \\ &= L_s(n) + U_{LM} L_s(n) = L_s(n+1) - U_{LM} L_s(n+1) \\ &= (1+U_{LM}) L_s(n) = GR(1-U_{LM}) L_s(n) \end{aligned} \tag{37}$$

Solving this expression for the maximum luminance uniformity tolerance U_{LM} that just corresponds to grey shade overlap

$$U_{LM} = \frac{\delta L_M}{L_s(n)} = \pm \frac{GR-1}{GR+1} \tag{38}$$

Providing a display having a fixed mean luminance, L(n), wherein all pixels have luminance variations satisfying $U_L < U_{LM}$ assures that no grey shade overlap will occur. Equations 36 and 37 have general validity since the grey shade index, n, can assume any positive integer value. Table 7 gives U_{LM} values corresponding to some possible grey shade ratios.

The non-overlap grey shade criteria establishes a bound on luminance variations only. Smaller variations in U_L would be required to provide grey scale separation. Thus for a grey scale ratio of $\sqrt{2}$, a U_L probability density distribution having a standard deviation of 10% or less would probably be a realistic goal to give good grey shade separation (i.e., even though some pixels could exceed the 17.2% overlap level).

TABLE 7

Luminance Uniformities Corresponding to Threshold Grey Shade Overlap Condition

GR	U_{LM}	U_{LM}%	Grey Shade Overlap Luminance
$\sqrt{2}$	.172	17.2	$L_{GO} = 1.172L(n) = .828L(n+1)$
1.5	.20	20	$L_{GO} = 1.20L(n) = .8L(n+1)$
1.63	.24	24	$L_{GO} = 1.24L(n) = .76L(n+1)$

6.4.5 Display Viewing Angle

Viewing angles of up to 45° from a normal to the display surface are desirable. Viewing angles of up to 30° are required.

6.4.6 Optical Crosstalk

Luminance optically coupled from an "on" pixel location to adjacent "off" pixel locations should produce an optically coupled difference luminance, ΔL_{OC}, at the "off" pixel satisfying the requirement

$$\Delta L_{OC} \leq 0.05\ \Delta L_p \tag{39}$$

where ΔL_p is the perceived difference luminance of the "on" pixel at the time ΔL_{OC} is measured. The requirement will be satisfied with only one pixel activated in the video array at a time.

6.4.7 Electrical Crosstalk

Emitted luminance produced by unaddressed pixels anywhere on the display surface and of sufficient luminance to be perceived as being partially "on", shall be considered to exhibit electrical cross-talk. The emitted luminance of electrical crosstalk pixels, ΔL_{EC}, shall satisfy the requirement

$$\Delta L_{EC} \leq 0.02 \Delta L_p \qquad (40)$$

where ΔL_p is the perceived difference luminance of "on" pixels elsewhere on the display surface at the time of the measurement.

6.4.8 Color Constancy and Uniformity*

The dominant wavelength is defined as the mean wavelength of the dot-matrix display pixels spectroradiometric light emission distribution. As the combined result of both increased ambient temperatures, of up to 71°C, and of 10,000 fc of incident ambient illumination, the dominant wavelength of the dot-matrix array should not shift by more than 70Å from its value at 25°C as measured in the dark. Color uniformity of emitted light from any area of the display surface should not vary from the mean dominant wavelength by more than ± 50Å. Color uniformity of reflected light shall meet the same criteria. Single or groups of four pixels or less will be energized while characterizing light emission color uniformity. Reflectance color uniformity measurements may be expanded in size to provide adequate measurement sensitivity.

6.4.9 Display Image Speed/Update Rate

To provide smooth image motion on an aircraft video display that is suitable for portraying high speed sensor-video and computer generated vector-graphic information (in either separate or overlayed formats), the Nyquist sampling criteria requires that sampling occur at a minimum of twice the highest image speed (i.e., expressed in pixels/second) that is to be accurately displayed. Human vision capabilities indicate image speeds as high as 20°/second (i.e., 10 inches/second at a 28 inch viewing distance) could be effectively made

*Subsequent analyses have resulted in the replacement of these requirements with more general criteria applicable to both color and monochromatic displays.

use of by a pilot using a 1024 line video display of nominally 125 pixels/inch resolution. This translates to a 1250 pixel/second at a 10 inch/second image speed and would therefore require a 2500 HZ sampling rate (i.e., equivalent to information update rate or picture frame image translation by no more than one pixel increments). A 250 HZ update rate should be considered a reasonable design goal for the first dot-matrix video display to be built and 60 HZ should be considered the minimum acceptable update rate.*

6.4.10 Pixel Defects

Tests to determine maximum numbers of discrete defects (i.e., continuously out or on pixels) and their distributions on the display surface have not been conducted. It is known that CRTs having a sufficient number of burn spots are replaced, although the replacement criteria appears to be pilot complaints, rather than any quantitative assessment of CRT performance. Since line defects are not acceptable on displays portraying graphics only information such defects would not be permissible on multipurpose displays either. Randomly distributed discrete defect levels of up to 1% appear to be acceptable for the portrayal of graphics information. Maximum acceptable defect levels for video information are likely to be under 0.1%, and like graphics having no defect clusters.

6.5 Conclusions

In this section, legibility requirements for dot-matrix displays have been presented that are certain to as a minimum match and possibly exceed the legibility capabilities of current military aircraft CRTs portraying video information. As was indicated in the introduction to this section, however, small critical detail dimension video information portrayed on dot-matrix displays is not perceived in the same way that

*1991 Notation. Practical aircraft electronic displays are at the present time limited by both technology and cost to refresh rates of nominally 60 Hertz for graphics and 60 fields/second for 2:1 interlaced video, these being the minimum rates required to produce acceptable flicker on nominal 5x5 inch area displays. Information update rates are characteristically 50 Hertz or less with 20 to 30 Hertz being more typical of the less maneuverable types of aircraft. The latter rates cause images moving at greater than about 0.25 inches/second to jump by perceptable amounts between successive update frames; however, the small amount of imagery actually required to move at these higher speeds together with the mitigating effects of the apparent image motion illusion have for all but a small percentage of applications resulted in pilot acceptance of displays operated at these lower rates.

the continuous spatial images portrayed on CRTs are perceived. In particular, when the difference luminance ΔL of a pixel is held constant the percent active area of the pixels can be reduced to 20% without degrading the legibility of small critical detail dimension video imagery portrayed on dot-matrix displays, provided the pixel's active dimensions do not decrease below 0.7 arc minutes.

On 125 pixel/inch (i.e., 8 mil pixel spacing) dot-matrix displays for instance, the minimum pixel size of 5.6 mils would govern and minimum percent active areas of 49% for square pixels or 38% for circular pixels could be used with no compensation in the pixel difference luminance/contrast from the 100% active area, 8 mil square pixel dimension display case. A dot-matrix display built in this manner would require higher pixel difference luminance values than a comparable 100% active area display under reduced pilot light adaptation conditions (i.e., below about 2,000 fc) as a result of the decrease in the pilot's visual acuity as the illuminance of the viewing environment decreases. For the display used in the example this would result in its difference luminance values being reduced at a slower rate than for a comparable display having 100% active area pixels.

As previously stated, the problem with this approach is that when the pilot uses the video display to monitor situation data rather than for target detection, recognition or identification, a display having the 49% and 38% active areas of the example, would result in perceived image luminance levels of 49% and 38% respectively that which would be present on a 100% active area display. The unanswered question is would this result in reduced pilot performance? Unfortunately studies that would provide an unambiguous answer to this question have not as yet been performed. It should be noted, however, that the evidence which does exist favors the proposition that acceptable pilot performance would be maintained for the example case in point and probably also for still lower percent active areas.

Referring to Figure 4 it may be seen that constant difference luminance/contrast CRT video imagery (i.e., and therefore 100% active area dot-matrix imagery) result in linearly increasing display luminance to threshold luminance ratios as the critical detail dimensions of the characters, targets and scene reference information making up the video display pattern increase in size. It should also be noted that the intersection of the extended CRT video image luminance/contrast line and the threshold legibility lines play a large role in determining how small a target critical detail dimension can be at the time when recognition or identification occurs. Increasing contrast beyond the $\Delta L/L_D = 4.6$ level shown in Figure 4 would result in smaller critical detail dimensions becoming discernible, while reducing contrast has the opposite effect. The remainder of the CRT contrast curve, which is applicable to higher legibility, larger critical detail dimension portions of the video image scene portrayed, is automatically and involuntarily established by the contrast selection made for the smallest critical detail dimensions the CRT is capable of portraying, given its resolution and image quality capabilities.

The point here is that there are valid reasons to believe that it may not be necessary to compensate dot luminance differences/contrasts for the less than 100% active areas associated with practical implementations of dot-matrix displays. Unfortunately the assertion cannot be made with complete certainty, in that practical user validation experiments have not been conducted and for that reason it has been necessary to use the more conservative specification approach for the video image legibility requirements given in this section.

It should be noted that the need to portray graphic display imagery at the spatially averaged perceived luminance levels shown in Figure 4 would place a lower limit on dot-matrix video display active area requirements below which pixel luminance would have to be increased to provide adequate graphics legibility. The smallest alphanumeric character to be displayed again establishes the minimum perceived contrast requirement. The perceived contrast of 2.7 for the $h_c = 0.098''$ F-18 alphanumeric set therefore establishes a video display percent active area limit of 59% (i.e., 2.7/4.6x100), before dot contrasts would have to be increased above average CRT values to maintain graphics image legibility. Even the 2.7 perceived contrast requirement is however predicated on experiments conducted on characters having critical detail dimensions of greater than 7 arc minutes leaving unanswered the question of how small these characters can become before the transition to full difference luminance perception of the pixels forming them occurs. In other words the perceived luminance requirements for the F-18's two smallest CRT characters, the $h_c = 0.098''$ and $0.117''$ character sets, could be somewhat higher than they would have to be if portrayed on a dot-matrix display. As has been done throughout this dot-matrix display legibility requirements assessment, where two possible interpretations exist, the one certain to provide adequate legibility has been selected.

APPENDIX A

CRT Luminance Requirements and Measurement Criteria

1. Contrast Definitions

Human Factors

$$C = \frac{L_S - L_D}{L_D} = \frac{\Delta L}{L_D} \qquad \text{(A-1)}$$

CRT Specifications

$$C = \frac{L_S}{L_D} \qquad \text{(A-2)}$$

2. Measurement Technique

Align a luminance measurement slit along raster or stroke written line length and scan across the line. The goal of this measurement is to have a slit width equal to one tenth or less than the half intensity line width of the line being measured. In practice the slit can be closer to one fourth of the CRT line width (i.e., defined as the distance between half intensity points on the line).

3. Contrast Determination Technique[1]

Equation A-2 is used to specify contrast in DoD procurement specifications. The symbol image luminance, L_S, used in the equation is the maximum luminance determined as a result of scanning across the single illuminated stroke or raster written line being measured. The background luminance, L_D, used in Equation A-2 is measured at a distance of no greater than 0.125 inches from the energized portion of a symbol formed with either stroke or raster written lines. The symbol luminance, L_S, and background luminance, L_D, are both measured with the symbol energized and with an illuminance of 10,000 fc incident on the display surface. The F-16 Radar EO display is measured with the display illuminated by a lighting sphere.

The specification does not state a criteria for measuring the 0.125 inch maximum distance from the energized portion of the CRT line. The half intensity points would be the largest line width that could reasonably be interpreted as "energized" by the CRT electron beam and should therefore be considered reasonable references for the measurement.

[1]Data content based on a conversation with Mr. Harry Waruszewski, ASD/ENAIC, on 16 May 1980.

4. Specifications for F-15 Vertical Situation Display (VSD)

4.1 Introduction

The F-15 VSD is a combined raster and stroke written display which utilizes the flyback period between raster fields to stroke write. Stroke writing therefore occurs with a 60 Hertz update/refresh rate, whereas video update is at the 30 HZ frame rate.

4.2 Stroke Written Line Width

The half intensity line width of the F-15 VSD symbology is specified as 10 mils + 5 mils - 0 mils where the +5 mils is a result of defocusing when higher intensities required for legibility in 10,000 fc are required.

4.3 Minimum CRT Luminance

A minimum luminance of 2,000 fL emitted from the face of the CRT was required. This requirement for the narrow spectral emission spectrum of the P-43 phosphor allows the use of a 13% peak transmittance green bandpass filter. Optical filtering results in an approximately 25 fL reflected luminance display surface when 10,000 fc is incident on it with about 200 fL of luminance emitted through the optical filter.

4.4 Display Active Area

The F-15 VSD has active screen dimensions of 3.84" x 3.84".

4.5 Contrast Specifications for Stroke Written Display Imagery

A minimum contrast ratio of C = 5.0 as calculated using Equation A-2 is required in a 10,000 fc illuminance environment as measured normally incident on the display surface. This results in an equivalent difference luminance as given by Equation A-1 of

$$\Delta L = L_S - L_D = 5L_D - L_D = 4L_D \tag{A-3}$$

or

$$C = \frac{\Delta L}{L_D} = 4 \tag{A-4}$$

in terms of the contrast formulation considered most suitable for relating to human visual requirements.

The F-15 VSD display was the first USAF CRT on which the pilots considered the stroke written symbology to be adequately legible. This means the contrast ratio for this display (C = 5) is suitable for use as a standard of comparison against which an at-a-glance viewing of graphics display imagery can be judged. The stroke written graphics of the F-15 VSD uses "off" plus three higher shades of grey as a means of intensity coding display information. The contrast ratio of five corresponds to the top grey shade.

4.6 Grey Shade Specification for Raster Written Imagery

The F-15 VSD was specified to have six $\sqrt{2}$ shades of grey (i.e., counting off as one) in a 10,000 fc viewing environment, or a maximum contrast ratio of 5.6. The P-43 phosphor CRT used in the F-15 actually produces eight $\sqrt{2}$ grey scale levels (i.e., again counting off as one) in 10,000 fc. Since this is the maximum number of grey shades the display electronics are designed to produce, the F-15 display may be considered to be fully legible in a 10,000 fc viewing environment.

4.7 Display Resolution

Measured horizontally the F-15 VSD has 110 line pairs per inch (i.e., 220 black and white lines per inch). This resolution is measured by anning a slit photometer, as described in Paragraph 2, over an image generated by a square wave modulated signal in the horizontal direction. Luminance peak to valley values corresponding to a 10% modulation were used as the resolution criteria. Relative modulation is given by the relationship[2]

$$M = \frac{L_S - L_D}{L_S} \qquad \text{(A-5)}$$

where L_S is the peak line luminance and L_D is the minimum valley luminance (i.e., black line minimum value). A 10% modulation (M = 0.1) yields a peak to valley difference luminance of $\Delta L = 0.111\ L_D$. When the modulation of the screen satisfies this condition, the number of black and white lines on the screen is counted to determine the maximum resolution the display is capable of producing.

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[2]Based on a conversation with Mr. Ronald Vokits, ASD/AXT, on 28 May 1980 and verified by Mr. Richard Miller, ASD/F-16 SPO, 30 May 1980 and the published literature.

It should be noted that at 110 line pairs/inch, a line pair (i.e., black and white repetition interval) is 9.09 mils wide, that is, narrower than the 10 mil diameter minimum half intensity spot diameter of the raster scanned CRT spot. It should also be noted that the modulation criteria, M = 0.1, results in a peak to valley difference luminance, $\Delta L = 0.111\ L_D$, whereas $0.41\ L_D$ is the difference luminance corresponding to a one grey shade luminance change. A 91.2% modulation, M = .912, would be required to go from the 1st to 8th grey shades on adjacent lines.

In the vertical direction the only specification on the F-15 raster pattern is that it be a 525 line 2:1 interlaced display system. The actual number of scanned raster lines would be less than this, but is typically not less than 480 lines per active area screen height.

4.8 Alphanumeric Character Height[3]

Graphic character dimensions on the F-15 CRT displays are specified in units of Bits where the height of the display 3.84 inches represents 1024 Bits. The only alphanumeric character font size used on the F-15 VSD consists of 20x36 Bits. This font size converts to font dimensions of 0.075"x0.135" on the face of the CRT. These dimensions correspond to the $W_c x h_c$ dimensions shown in Figure 1.

The F-15 JTIDS display which is to be nominally 5"x5" in active area is to have a 12x22 Bit, 0.059"x.107" alphanumeric character set which is smaller than the character font sizes tested in the JTIDS program to date. With the installation of the JTIDS display a new F-15 Programmable Signal Data Processor will be installed that will expand the F-15 VSD symbol set from 40 to 136. It will contain both the VSD and JTIDS alphanumeric symbol sets.

5. Specifications for F-15 HUD[1]

The F-15 HEAD Up Display (HUD) has a stroke written CRT image source that can produce as a minimum from its glass image combiner a reflected luminance of 1000 fL. The HUD symbology is portrayed using lines which subtend 1 milliradian (mr) + 1/2 mr - 0.3 mr at the pilot's eyes. The half intensity line width variations allow portraying different symbology in different line widths, and some tolerance for maximum intensity blooming of the CRT spot diameter.

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[3]Based on a conversation with Mr. William Soukup, ASD F-15 SPO.

6. Specifications for F-16 Radar/EO Display

6.1 Introduction[4]

The F-16 Radar/EO display is a raster only display with both video and graphics generated by raster writing. The display uses a 6-7 mil half intensity diameter spot (i.e., CRT production variation) P-43 phosphor CRT (i.e., spot expands to 8.5-10 mils under 10,000 fc drive condition) having active area dimensions of 4"x4".

6.2 Minimum CRT Luminance[1]

The minimum through the filter emitted luminance specified for this display is 200 fL. This luminance was chosen in part as a means of overcoming the effects of veiling luminance levels induced in the pilot's eyes during exposure to glare sources such as the sun.

6.3 Contrast/Grey Shade Specification[1]

The F-16 display was specified to have six $\sqrt{2}$ ratio grey shades in a 10,000 fc viewing environment (i.e., "off" is counted as the 1st grey shade). This contrast requirement had to be demonstrated during tests performed in a lighting sphere with 10,000 fc illuminance incident on the display surface. This could be a considerably more severe test environment than that employed for the F-15 VSD if it is used to produce a combined specular/diffuse reflectance from the display surface.

Graphic symbology overlayed on the raster imagery was to have a minimum contrast ratio, $C = L_S/L_D$, of 7:1 under the foregoing test condition. The intent of this requirement was to make the graphic imagery legible against the brightest video imagery that could be present simultaneously on the display surface.

6.4 Display Resolution[4]

The F-16 Radar/EO Display was built to provide a vertical resolution of 121 lines/inch and a horizontal resolution of 101 line pairs/inch both measured using a 10% modulation criteria. The central 1.5" radius area satisfies this criteria. Outside this area a 2% modulation criteria is satisfied. Ten percent modulation (i.e., $M = .1$) when substituted into Equation 5 gives a difference luminance

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[4]Based on conversations with Mr. Richard Miller, ASD/F-16 SPO, on 29 and 30 May 1980.

of $\Delta L = 0.111\ L_D$ between the modulation pattern peaks and valleys. Two percent modulation gives a peak to valley difference luminance of $\Delta L = 0.0204\ L_D$. Raster video corresponding to 875 line sensor data is also portrayed on the F-16 display.

6.5 Alphanumeric Character Height[4]

Graphic character dimensions on the F-16 Radar/EO display are specified in Bits where the height of the display, 4.0 inches, represents 482 Bits. The only alphanumeric character size portrayed on the F-16 Radar/EO display is composed of 14x18 bits. This character size converts to CRT display face dimensions of 0.117"x0.149". The information for generating the alphanumeric character fonts is stored in a 7x9 dot-matrix format. The character dimensions given above correspond to the $W_c x h_c$ dimensions shown in Figure 1.

7. Specifications for the F-18 CRT Displays[5]

7.1 Introduction

During its flight test phase the F-18 has been equipped with three 5"x5" active area P-43 phosphor CRT displays. One of these is to be replaced with a 5 1/2" x 5 1/2" active area graphics annotated projected moving map HSD in the operational versions of the aircraft. Pilot's testing these aircraft have reported good display legibility for both graphics and video information. The F-18 CRTs utilize a combination of raster and stroke writing. Stroke written information is updated during the flyback period between the 2:1 interlaced raster fields. Stroke writing therefore occurs at a 60 Hertz update/refresh rate, whereas video information is updated at the 30 HZ frame rate.

7.2 Stroke/Raster Written Line Width

The half intensity line width of the F-18 displays is specified as 8 mils maximum for both the stroke written and raster written lines. Testing has verified this was achieved.

7.3 Contrast Specifications for Stroke Written Display Imagery

A minimum contrast ratio of C = 5.6 as calculated using Equation A-2 is required in a 10,000 fL integrating sphere luminance test environment. This test is like the one performed on the F-16 CRT

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[5]Data content based on a conversation with Mr. Norm Martens, F-18 Avionics, McDonnell Douglas, on 16 May 1980.

display. It results in 10,000 fc of illuminance incident on the display surface but it produces a higher diffuse reflected luminance from the display for a sun gun would for angles of incidence of 30° or greater from the display surface normal. The severity of the test results from the fact that the illuminance incident at angles up to about 30° from the normal stimulates a much larger diffuse reflectance component than does an equal amount of illumination incident from angles greater than 30°. When graphics and video are overlayed the graphics is to be depicted at one grey shade above the highest video grey shade.

7.4 Minimum CRT Luminance

The minimum difference luminance emitted through the filter on the F-18 multipurpose displays must be 200 fL at a minimum contrast ratio of 5.6 (i.e., as calculated using Equation A-2).

7.5 Phosphor Persistence

The time required for the CRT spot brightness to fall from 100 fL to 10 fL shall not exceed 2 milliseconds.

7.6 Grey Shade Specification for Raster Written Imagery

The F-18 CRTs are capable of portraying six $\sqrt{2}$ grey shades (i.e., counting no image as one) in the 10,000 fL surface luminance integrating sphere test environment, for a maximum contrast ratio of 5.6 when calculated using Equation A-2. The CRT display's contrast control allows reduction of the ratio between all of the adjacent grey shade levels below the $\sqrt{2}$ maximum ratio. The control of contrast is moreover to be continuously variable throughout the useable range of display brightness. This includes the one higher grey shade used for the maximum graphics imagery luminance level. The display's brightness control is to vary brightness continuously and so that a linear change in the control position will produce a perceived linear change in image brightness (i.e., with grey scale contrast held constant). The displays are also equipped with an automatic contrast control that provides a linear change in contrast between 12 at 100 fc of illuminance and 5.6 at 10,000 fc as ambient conditions change. Below 100 fc the display must be controlled manually.

In subdued ambient illumination conditions the displays are capable of providing up to eight $\sqrt{2}$ ratio grey shades (i.e., again counting no image, the background luminance, L_D, as the first grey shade). This requirement is equivalent to a difference or emitted luminance requirement for ΔL of $\Delta L = (\sqrt{2}^{\,7} - 1)L_D$ for eight grey shade video imagery, that is, the maximum difference luminance

$$\Delta L = 10.3\ L_D \tag{A-6}$$

is required for video or

$$\Delta L = L_S - L_D = (\sqrt{2}^{\,8} - 1)L_D = 15L_D \tag{A-7}$$

for graphics superimposed on video. It should be noted that grey shade selection for graphics is the same as for video.

7.7 Display Resolution

The F-18 CRT displays were built to provide equal vertical and horizontal resolutions of 120 line pairs/inch both measured using a 5% modulation criteria (i.e., see Equation A-5 with $M = 0.05$). Five percent modulation gives a difference luminance of $\Delta L = .0526\ L_D$ between peaks and valleys of the CRT line pattern when the number of square wave generated line pairs is counted.

7.8 Alphanumeric Character Height

Graphic character dimensions on the F-18 CRT displays, including the HUD are specified in units of Display Increments (DI) where the height of the display represents 1024 DIs. The minimum height alphanumeric characters have dimensions of 12x20 DIs which for a 5 inch high CRT screen active area yields character dimensions of 0.059"x0.098" or nominally 0.1 inches in height. Including the 0.1 inch alphanumeric character set there are four complete sets of alphanumeric characters that can be called upon to build a display format. The other alphanumeric character sets are 120% larger than the minimum size (i.e., 0.117 inches high), 150% larger (i.e., 0.146 inches high) and 200% larger (i.e., 0.195 inches high). The 0.117 inch high alphanumeric character set is the most frequently used.

The character generator also provides a wide variety of smybolic characters, most of them larger than the alphanumeric character sets, and one set of 30x50 DI, 0.146"x0.244" numeric characters. One function of flight test had been to evaluate the character sizes that were selected apriori for use in the F-18's multipurpose display information formats. While the sizes of characters used have been selectively increased in some instances, overall the changes have small, and few additional changes are expected. The 0.146 inch character height is used for the presentation of caution and advisory signal information in the F-18. This information is duplicated on backup standard signal annunciator indicators.

APPENDIX B

Example Calculation of Perceived Luminance

The F-15 VSD has one set of 0.135 inch high alphanumeric characters that are used for constructing all of the display's information formats. Since pilots flying the aircraft consider the display to be legible, its measured difference luminance

$$\Delta L = 4L_D \qquad \text{(B-1)}$$

may be taken as a baseline requirement for alphanumeric character legibility in a 10,000 fc aircraft viewing environment. The reflected display background luminance, L_D, from the F-15 VSD in a 10,000 fc illuminance environment is 25 fL, therefore the requirement of Equation B-1 gives an emitted luminance requirement of ΔL = 100 fL.

In Figure 1 the dashed line represents the trace of the center of the CRT written line used to form a character and the distance, h_c, corresponds to its height specification. The objective here will be to calculate the difference luminance for an ideal uniform luminance character shown in Figure 1 that would cause both characters to be perceived as being equally legible. Calculating the perceived luminance, ΔL_p, for the ideal character using Equation 6 with Equation 7 substituted for the spatial luminance distribution of the CRT line is exact only if the critical detail dimension of the two characters is held fixed when the stroke width is changed. Comparing characters having the height parameter, h_c, held fixed requires compensation for changes in the character critical detail dimensions and hence their perceived heights.

Table B-1 summarizes the dimensional relationships applicable to ideal and CRT written alphanumeric characters. It should be noted that the comparisons between the CRT written characters and the ideal characters can at maximum result in a critical detail dimension decrease of 35.3% in going from an infinitesimal CRT line width to an ideal character, SW_I, line width for equal height, h_c, comparison characters.* The very strong dependence of character legibility on its critical detail dimension, cd, is therefore limited to a second order error effect by the limited cd magnitude change possible.

*1991 Notation. Based on an ideal character with a 0.15h stroke width.

TABLE B-1

Alphanumeric Character Dimensional Relationships

Ideal Characters

$$SW_I = .15h = .176h_c = .5455cd$$

$$h = h_c + SW_I = 1.1765h_c = 6.6667SW_I$$

$$cd = \frac{h - 3SW_I}{2} = .2750\,h = 1.833SW_I = .3236h_c = \frac{h_c - 2SW_I}{2}$$

CRT Characters

$$SW \triangleq 4\,\sigma \quad \text{Visually Perceptible Line @ 13.5\% of } \Delta L \text{ (Peak)}$$

$$h = h_c + 4\,\sigma$$

$$cd = \frac{h - 12\,\sigma}{2} = \frac{h_c - 8\,\sigma}{2}$$

$$cd \rightarrow \frac{h_c}{2} = .5h_c \text{ as } \sigma \rightarrow 0$$

As an example of the magnitude of this error consider the comparison of an ideal character with another character of height, h_c, uniform luminance and having a stroke width of $SW_I/4$. Straight luminance averaging using Equation 5 gives

$$\Delta L_p = \frac{1}{SW_I \ell} \left[\frac{SW_I}{4} \ell \right] \Delta L = .25 \Delta L \tag{B-2}$$

Experimental testing shows that an additional $\sqrt{2}$ increase in luminance of the comparison ideal character

$$\Delta L_p = .25 \sqrt{2} \ \Delta L = .35 \Delta L \tag{B-3}$$

would be required to compensate for the reduction in the ideal character's critical detail dimension and thereby give equal perceived legibilities. In Equation B-3, ΔL is the measured difference luminance of the narrower stroke width character and ΔL_p is the measured difference luminance of the ideal character. In the same experiment it was found that a character having a stroke width of 73% of the ideal character stroke width required no compensation for the small change in critical detail dimension in that $\Delta L_p = .73 \Delta L$ produced equal character legibility.

One convenient method of calculating perceived luminance using Equation 6 with Equation 7 substituted for $\Delta L(x)$ is the use of mathematical tables for the standard Normal Probability Function.

By making the change of variables

$$x = \sigma u \tag{B-4}$$

in Equations 6 and 7 we may write the perceived luminance equation as follows:

$$\Delta L_p = \frac{2\sqrt{2}\,\pi\,\sigma}{SW_I} \left[\int_{-\infty}^{\frac{SW_I}{2\sigma}} \frac{\Delta L(u)}{\sqrt{2\pi}} du - \int_{-\infty}^{0} \frac{\Delta L(u)}{\sqrt{2\pi}} du \right] \tag{B-5}$$

where

$$\Delta L(u) = \Delta L \exp \left[- \frac{u^2}{2} \right] \tag{B-6}$$

Due to the symmetry of the Gaussian line about its center Equation B-5 was formed to give twice the integral from 0 to $SW_I/2\,\sigma$. Equation B-5 reduces to

$$\Delta L_p = \frac{2\sqrt{2\pi}\,\sigma}{SW_I} \left[\int_{-\infty}^{\frac{SW_I}{2\sigma}} \frac{\Delta L(u)du}{\sqrt{2\pi}} - 0.5\Delta L \right] \tag{B-7}$$

upon substituting for the last term using the probability function tables. The remaining integral on the right may be evaluated using the appropriate ideal character stroke width from Equation 4, the standard deviation values from Table 1, and the probability function numerical tables. Letting

$$U = \frac{SW_I}{2\sigma} \quad \text{and} \quad \Phi(u) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{u^2}{2} \right] \tag{B-8}$$

Equation B-5 becomes

$$\Delta L_p = \frac{\sqrt{2}\pi}{U} \; \Delta L \left[\int_{-\infty}^{U} \Phi(u)\,du - 0.5 \right] \tag{B-9}$$

where $\Phi(u)$ is the normal function in standard form.

Values of the parameters used in Equations B-8 and B-9 to calculate the perceived luminance of an equivalent ideal character are consolidated from elsewhere in the report into Tables B-2 and B-3. In addition these tables contain the calculated values of the CRT character critical detail dimension expressed in both thousandths of an inch (mils) and in subtended minutes of arc (assuming a 28 inch viewing distance). The critical detail dimension of the raster and stroke written CRT characters were calculated using the equation in Table B-1. The selection of the CRT character visual line width as $SW \approx 4\sigma$ (i.e., see Figure 2) is based on the fact that the low luminance of the tails of the normal distribution make them illegible when a character is viewed as a whole and therefore do not contribute to the perceived stroke width of the CRT line.

In evaluating Equation B-9 for the aircraft CRT parameters in Table B-2 the product term containing the integral can be approximated as 0.5 with an error of less than 1.2% for values of the integration limit U satisfying $U \gtrsim 2.5$. In this limit the perceived luminance of an equivalent ideal character can be expressed simply as

$$\Delta L_p \approx \frac{\sqrt{2\pi}}{2U}\ \Delta L = \frac{\sqrt{2\pi}\ \sigma}{SW_I}\ \Delta L = \frac{14.2\ \sigma}{h_c}\ \Delta L \qquad \text{(B-10)}$$

the final form being expressed entirely in terms of CRT display parameters. The only display not satisfying the U [illegible] dition, the F-15 VSD set for sunlight viewable operation, [illegible] have predicted a perceived luminance 6.2% higher than the actual value had the approximation of Equation B-10 been used.*

*1991 Notation. For the purpose of calculating CRT display character difference luminance requirements, which are equivalent to those of ideal continuous stroke characters, a stroke width equal to 15% of the ideal character height, h, has been used in this appendix. This stroke width was chosen because increasing this dimension from 15 to 20% does not cause a further increase in the character difference luminance requirement (i.e., with the character critical detail dimension held fixed), while decreasing the stroke width from 15% to 12% does cause a gradual, albiet marginal increase in the luminance required to maintain legibility at a constant value.

TABLE B-2

Perceived Luminance Calculation Data for Ideal Characters (Character Height: h_c = Constant) Under Room Ambient CRT Drive Conditions

	h_c in mils	σ in mils	$SW=4\sigma$ in mils	SW_I $=.1765h_c$ in mils	h $=h_c+4\sigma$ in mils	cd(mils) $=(h_c-8\sigma)/2$ α_c(Arc Min)	cd_I(mils) $=.3235h_c$ α_c(Arc Min)	$\frac{\Delta L_p}{\Delta L}$ Eq. B-9	$\frac{\Delta L_p}{L_D}$	U $=\frac{SW_I}{2\sigma}$
F-15 $\Delta L=4L_D$	135	4.25	17.0 $=.71SW_I$	23.8	152	50.5 6.2'	43.7 5.4'	0.445	1.78	2.80
F-16 $\Delta L=4.6L_D$	149	2.55	10.2 $=.39SW$	26.3	159	64.3 7.8'	48.2 5.9'	0.243	1.12	5.16
F-18	98	3.40	13.6 $=.78SW_I$	17.3	112	35.4 4.4'	31.7 3.9'	0.487	2.24	2.54
$\Delta L=4.6L_D$	117	3.40	13.6 $=.66SW_I$	20.6	131	44.9 5.5'	37.8 4.7'	0.413	1.90	3.03
	146	3.40	13.6 $=.53SW_I$	25.8	160	59.4 7.3'	47.2 5.8'	0.330	1.52	3.79
	195	3.40	13.6 $=.39SW_I$	34.4	209	83.9 10.3'	63.1 7.75'	0.248	1.14	5.06
	244+	3.40	13.6 $=.32SW_I$	43.1	258	108.4 13.3'	78.9 9.7'	0.198	0.91	6.34

+Numeric character set

TABLE B-3

Perceived Luminance Calculation Data for Ideal Characters (Character Height: h_c = Constant) Under 10,000 fc Illumination CRT Drive Conditions

	h_c in mils	σ in mils	$SW=4\sigma$ in mils	SW_I $=.1765h_c$ in mils	h $=h_c+4\sigma$ in mils	cd(mils) $=(h_c-8\sigma)/2$ α_c(Arc Min)	cd_I(mils) $=.3235h_c$ α_c(Arc Min)	$\frac{\Delta L_p}{\Delta L}$ Eq. B-9	$\frac{\Delta L_p}{L_D}$	$U = \frac{SW_I}{2\sigma}$
F-15 $\Delta L=4L_D$	135	6.37	25.5 $7SW_I$	23.8	161	42.0 5.2'	43.7 5.4'	0.630	2.52	1.87
F-16 $\Delta L=4.6L_D$	149	3.93	15.7 $=.60SW_I$	26.3	165	58.8 7.2'	48.2 5.9'	.374	1.72	3.35
F-18	98	4.25	17.0 $=.98SW_I$	17.3	115	32 3.9'	31.7 3.9'	.589	2.71	2.04
$\Delta L=4.6L_D$	117	4.25	17.0 $=.83SW_I$	20.6	134	41.5 5.1'	37.8 4.7'	.510	2.35	2.42
σ(10 mil spot) =4.24	146	4.25	17.0 $=.66SW_I$	25.8	163	56 6.9'	47.2 5.8'	.411	1.89	3.04
mils	195	4.25	17.0 $=.49SW_I$	34.4	212	80.5 9.9'	63.1 7.75'	.309	1.42	4.05
	244+	4.25	17.0 $=.39SW_I$	43.1	261	105 12.9'	78.9 9.7'	.247	1.14	5.07

+Numeric character set